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SCIENCE AND EDUCATION ADMINISTRATION
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Five watersheds, ranging in size from 29 to 49 acres, were instrumented in East-Central Ohio to investigate the hydrologic and water quality conditions occurring before, during, and after surface mining. Physical information was obtained for each watershed, and instrumentation was installed for obtaining hydrologic and weather data and water quality samples.

Premining ground-water systems for each watershed were found to have two major perched aquifers within the top 250 feet. Shallowest ground water is commonly of the calcium bicarbonate type; whereas, water in the deeper aquifers is of variable type. Although dissolved-solids concentration is generally 200-600 mg/l, brackish or salty water is present in several areas.

A one-dimensional unsaturated flow model was developed to interface with a quasi-three-dimensional ground-water model as part of a composite hydrologic model. The unsaturated flow model includes provisions for an evapotranspiration model.

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The average concentrations of the water quality parameters for the premined watersheds were as low or lower than the EPA recommended maximum allowable concentrations in drinking water. The average concentration of suspended solids in storm runoff ranged from 118 to 1110 mg/l, and for base flow the range was from 44 to 247 mg/l; the higher concentrations were associated with the watersheds exhibiting the greatest premining disturbance. Iron ranged from an average of less than 3 μg/l to 228 μg/l. Manganese ranged from less than 41 μg/l to 334 μg/l.

Soils on each watershed were mapped and samples obtained. Laboratory analyses on most of the samples have been performed. The major soil series according to the surveys were Gilpin, Westmore, Dekalb, and Westmoreland.

An analyses was made of one of the costs of reclaiming coal mines; the legal and administrative costs of complying with legislation. Such costs borne by coal companies under the Ohio law are thought to be a surrogate of these costs under the new Federal law. Regression analyses were used to relate the legal and administrative costs to permit acres and tonnage of coal.

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RESEARCH ON THE HYDROLOGY AND WATER QUALITY OF WATERSHEDS SUBJECTED TO SURFACE MINING

PHASE 1:

PRE-MINING HYDROLOGIC AND WATER QUALITY CONDITIONS

Prepared for

UNITED STATES DEPARTMENT OF INTERIOR
BUREAU OF MINES

by

UNITED STATES DEPARTMENT OF AGRICULTURE
SCIENCE AND EDUCATION ADMINISTRATION
FEDERAL RESEARCH
NORTH APPALACHIAN EXPERIMENTAL WATERSHED
COSHOCTON, OHIO

and

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WOOSTER, OHIO

Interim Report: Jan. 22, 1976 — Jan. 22, 1978

on

Contract Nos.: JO166054 (OARDC)
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July 22, 1978

FOREWORD

This (joint) report was prepared by the USDA-Science and Education Administration-Agricultural Research, North Appalachian Experimental Watershed, Coshocton, Ohio and the Ohio Agricultural Research and Development Center, Wooster, Ohio under USBM Contracts J0166055 (USDA-SEA-AR) and J0166054 (OARDC). The contracts were initiated under the Mining Environmental Research Program. They were administered under the technical direction of the Denver Mining Research Center with Mr. Gary McIntosh acting as the Technical Project Officer. Mr. Francis M. Naughton was the contract administrator for the Bureau of Mines.

The Phase I report, concerning premining hydrologic and water quality conditions, is a summary of the work completed under these contracts during the period January 22, 1976 to January 22, 1978.

The contracts were awarded for conducting the research as proposed in a document presented jointly by the USDA-SEA-AR, North Appalachian Experimental Watershed and the Ohio Agricultural Research and Development Center: A Research Proposal--Research on the Hydrology and Water Quality of Watersheds Subjected to Surface Mining (May, 1975). The U. S. Geological Survey, the Soil Conservation Service, the Muskingum Watershed Conservancy District, the Utah State University, and three private mining companies are participants in the studies.

DISCLAIMER NOTICE

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Interior Department's Bureau of Mines or of the U. S. Government.

PREFACE

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ABSTRACT

Five watersheds, ranging in size from 29 to 49 acres, were selected in East-Central Ohio to investigate the hydrologic and water quality conditions occurring before, during, and after surface mining. Four of the watersheds will undergo surface mining, involving either the Number 6, 9, 11, or 8 coal seams, and one watershed having an outcrop of the Number 6 coal will be operated as a control watershed.

To determine the premining hydrologic and water quality conditions (Phase 1), physical information was obtained for each watershed and instrumentation was installed for obtaining hydrologic data and water quality samples.

In addition to topographic maps, soils and vegetation maps were prepared. Stratigraphic columns were developed from geologic cores; networks of observation wells and of soil moisture access tubes were installed; and weather stations were established to measure temperature, humidity, wind and solar radiation, and to collect precipitation samples.

Field data were collected over a 10-month period for one watershed and for about 8 months on another watershed before surface mining began. The other watersheds continued in the premining data phase. These data were for precipitation, temperature, relative humidity, wind speed, solar radiation, snow and frozen soil, soil moisture, infiltration (rainfall simulator), spring discharge, runoff from watersheds, and ground-water levels. Also, samples of runoff and ground water were obtained for chemical analyses and additional samples of runoff were acquired for suspended sediment load determinations.

Over the study period, precipitation was not very representative of the long term averages, but data are available from the control watershed for a representative 7 year period which should prove invaluable in modeling the hydrology of the project watersheds for the premined conditions.

Spring discharges (before mining) from the upper aquifer of two of the watersheds averaged only 508 and 652 gallons daily. The proportion of precipitation occurring as surface runoff from the large watersheds ranged from 8 to 36 percent and the peak discharges from 5.86 to 81.95 cfs.

Base-flow and runoff water samples from four of the watersheds (unmined conditions) were collected and analyzed quantitatively for 39 water quality parameters. Monthly precipitation samples and sediment fractions of the base flow and runoff were analyzed for 22 and 17 parameters, respectively.

The average concentrations of the water quality parameters for the watersheds (unmined), except for suspended solids, were as low or lower than the EPA recommended maximum allowable concentrations in drinking water. Several parameters in precipitation equaled or exceeded the levels of corresponding parameters in runoff water. The average concentration of suspended solids in storm runoff ranged from 118 to 1110 mg/l, and for base flow the range was from 44 to 247 mg/l; the higher concentrations were associated with the watersheds exhibiting the greatest disturbance. Iron ranged from an average of less than 3 µg/l to 228 µg/l. Manganese ranged from less than 41 µg/l to 334 µg/l.

Ground-water systems (unmined condition) are described for the five project watersheds. Each watershed was found to have two major perched aquifers within the top 250 feet. Generally, these perched aquifers involve local flow systems, though flow across watershed boundaries in some areas. Recharge is mostly from local precipitation and discharge is mostly as spring flow, base flow, evapotranspiration, and leakage through the underlying confining bed. Shallow ground water was commonly of the calcium bicarbonate type. Although dissolved-solids concentration was generally 200 to 600 mg/l, brackish or salty ground water was present in several areas.

A composite hydrologic model for the project watersheds will consist of separate ground-water, unsaturated flow, overland flow, and evapotranspiration component models. The ground-water model (a modified quasi-three-dimensional U. S. Geological Survey model) operates on a grid network and the newly formulated unsaturated flow model was divided into overlying prismatic elements for numerical solutions. The unsaturated flow model includes provision for incorporating the evapotranspiration model. An available distributed kinemetic overland flow model was utilized.

An analyses was made of one of the costs of reclaiming coal mines; the legal and administrative costs of complying with legislation. Such costs borne by coal companies under the Ohio law are thought to be a surrogate of these costs under the new Federal law. Regression analyses were used to relate the legal and administrative costs to acres in the permit and the tonnage of coal produced.

SUMMARY

Five watersheds, ranging in size from 29 to 49 acres, were selected in East-Central Ohio to investigate the hydrology and water quality conditions occurring before, during, and after surface mining. Four of the watersheds will be mined, and one will remain undisturbed for use as a control watershed. The Number 6 coal outcrops in the control watershed (A06) and the other watersheds will be involved in the surface mining of either Number 6, 9, 11, or 8 coal seams, designated as Watersheds C06, M09, J11, and J08, respectively. Such a selection was made because the different natural and mined geologic profiles would be reflected in different soils, in different surface and ground-water flow regimes, and in different water quality conditions.

To determine the premining hydrologic and water quality conditions (Phase I), as part of the overall study, physical information was obtained for each watershed, and instrumentation was installed for obtaining hydrologic data and water samples for quality determinations.

In addition to topographic maps, soils and vegetation maps were prepared from field survey data for all the project watersheds.

Using the county and state soil legends, a total of 26 different soils were delineated on the four watersheds which are to experience surface mining. Delineations on each watershed were differentiated on the basis of the soil series along with percent slope and degree of erosion. The five most extensive and representative soils of the Coshocton County site (C06) and the Muskingum County site (M09) were sampled and characterized for chemical and physical properties.

All the study watersheds were underlain by stratified sedimentary rocks of the Pennsylvanian System, consisting of shale, siltstone, sandstone, limestone, coal, and clay. The rocks were deposited in shallow marine or shoreline environments, then subjected to crustal uplift resulting in fracturing, a slight regional southeasterly dip, and subsequent partial erosion. Several feet of unconsolidated weathered rock or soil materials overly the bedrock in most places. Stratigraphic columns were developed from geologic cores obtained from all the study watersheds, and physical and chemical data were obtained for the cores from the four watersheds which are to experience surface mining.

Vegetation surveys were made on each of the project watersheds in their unmined condition. The data were translated into generalized maps of the major overstory vegetation types, basal area of vegetation, and of vegetative cover surrounding soil moisture access tubes.

For adequate evaluation of the hydrology and water quality aspects of watersheds subjected to surface mining, weather and surface and

subsurface hydrologic data are required. Also for modeling of watershed hydrology and water quality, spatial and temporal numerical descriptions of the hydrologic and water quality components are necessary. The hydrologic data collection system for each watershed was designed to meet these needs and consisted of the following features:

1. Weather instruments installed in or near the watershed, for measurement of precipitation (dual-gages for calculating actual precipitation), temperature, humidity, wind, incident and net solar radiation, and for obtaining samples of precipitation.

2. Sampling points (at weather station and elsewhere) for measuring depth and water content of snow and frozen soil conditions.

3. Networks of access tubes to accommodate a neutron probe for measurement of soil moisture to a depth of 51 inches.

4. Springs developed on the outcrop of the coal seams scheduled for mining and equipped with HS-flumes to measure discharge and to serve for collection of water quality samples.

5. Flow measuring structures (drop-box weirs where heavy sediment loads are expected) equipped with instrumentation for collecting both discrete and composite water samples.

6. Sediment ponds immediately downstream of study watersheds with the principle spillway consisting of a vertical pipe or a riser, equipped with a trash rack and anti-vortex device, joined to a pipe extending through the embankment and outletting into a concrete, impact basin. (An appropriate chute was constructed as part of the impact basin for operation of an H-flume to measure discharge from the pond. A Coshocton wheel sampler was used for collection of water samples, along with grab samples, for sediment and water quality determinations).

7. On small sub-watersheds, an H-flume, drop-box weir, or Parshall-flume installed to measure discharge and to serve as water quality sampling sites.

8. Observation well networks with wells drilled by the air rotary method and each cased so as to be open to only one of the three major saturated zones.

Major exceptions to the typical instrumentation design, as related to the five project watersheds, were only three small sub-watersheds, four weather stations, sediment ponds for three of the four watersheds scheduled for mining, limited wells and soil moisture access tube for watersheds scheduled for limited mining, and only three spring developments. For this report, no runoff or soil moisture data were available from the limited mining site (J08) because the instrumentation had not been installed.

Other instrumentation consisted of a portable rainfall simulator-infiltrometer that was used to determine infiltration characteristics of selected soils.

The period of premining record for each watershed, and for parameters for a watershed, varied as instruments were installed and mining progressed. In general, complete data for the premining conditions were obtained over a period of 10 months for Watershed C06 and about 8 months for Watershed M09. Such data are continuing to be collected for Watershed A06 (not to be mined) and for Watershed J11 (yet to be mined).

Precipitation occurring during the study period departed from the long-term average at the C06, M09, and J11 sites by <+1, -8, and +19 percent, respectively. For the longer period (30 months) at the A06 site, the departure was only +7 percent. In general, the seasonal precipitation was not very representative of the long-term averages.

The deepest snow measured was 11.5 inches at the M09 site in January, 1976; a maximum water content of 1.82 was also observed at the same time. The deepest frozen ground measurement was 8 inches at the C06 site in February, 1976.

Soil moisture data obtained to a depth of 51 inches exhibited by far the greatest changes in the 0 to 9-inch depth, reflecting recharge from precipitation and snowmelt, and discharge to evapotranspiration and percolation. The maximum changes in stored soil water for Watersheds C06, M09, J11, and A06 were 3.37, 1.85 3.46, and 4.35 inches, respectively.

Infiltration capacity data were obtained for three soils by use of a rainfall simulator-infiltrometer system. The time domain of infiltration was represented by a three-parameter equation, in the form of an analogous resistance-capacitance circuit. At application rates of 2.0 and 2.5 inches per hour, equilibrium infiltration rates of 0.56 and 1.32 inches per hour were reached in about 3 and 4 hours for the Coshocton and Gilpin soils, respectively. The time constant of the diminishing infiltration ranged from 0.24 to 1.0-hour.

Spring discharges at the C06, M09, and A06 sites were nearly constant for short periods of time and the average daily discharges were 652, 508, and 3,923 gallons, respectively. Maximum average daily discharges were 3,361, 2,068 and 28,694 gallons for sites C06, M09, and A06, respectively. Discharge ceased at M09 and became nearly zero at C06 in the late fall.

The proportion of precipitation occurring as surface runoff amounted to 30, 12, 8, and 36 percent for Watersheds C06, M09, J11, and A06, respectively. Peak discharges observed for the period were 5.86, 81.95, 6.31, and 13.80 cfs for Watersheds C06, M09, J11, and A06, respectively. Runoff from the small watersheds was rather low, ranging from less than one to only 4 percent of the precipitation. Runoff for the A06 control watershed was erratic during 1977 with a yearly excess of 13 percent over the long-term average.

Runoff under stable surface conditions was observed from 1967 through 1977 with a three-year break in the record from July 1972 through June 1975. These data should prove invaluable in modeling the hydrologic behavior of the project watershed for unmined conditions.

Base-flow and surface runoff water samples from the four watersheds (C06, M09, J11, and A06) were collected and analyzed quantitatively for 39 water quality parameters. In addition, sediment fractions of the base-flow and runoff, and monthly precipitation samples were analyzed for 17 and 22 parameters, respectively.

When data from base flow and surface runoff were compared for all watersheds, the concentrations of a number of parameters showed general trends. The average concentrations of aluminum, iron, manganese, and suspended solids in base flow were lower than in surface runoff while alkalinity, hardness, strontium, sulfate, and dissolved solids were higher. The largest difference was observed in suspended solids, which was clearly related to flow rate.

Considering the average concentrations of different water quality parameters in water samples from the four watersheds, it was evident that the concentrations were as low or lower than the recent (1977) U.S. Environmental Protection Agency recommended maximum concentrations in drinking water.

The analyses of monthly precipitation samples revealed that the concentrations of several parameters in precipitation equaled or exceeded the levels of corresponding parameters in runoff water.

The concentrations of the measured parameters from base-flow and surface-runoff sediment samples for Watersheds C06 and M09 were compared. With the exception of TOC, no concentration differences between base flow and storm runoff from the C06 site were noted. For the M09 site, however, except for cadmium, the concentrations of all constituents in the base-flow sediment fractions were higher than in storm runoff.

Suspended solids were determined from both base flow and storm-runoff events for Watersheds C06, M09, and J11, while in premined conditions, and from the control watershed (A06). The average concentrations of suspended solids in storm runoff were 870, 1110, 118, and 144 mg/l for Watersheds C06, M09, J11, and A06, respectively. In this sequence, base flow concentrations of 247, 157, 44, and 45 mg/l were observed. The amount of disturbance in the watersheds decreased in the same sequence. Watershed C06 experienced some road construction for installation of ground-water wells; M09 had not completely recovered from the development of a gas well which involved an access road; J11 had a gravel road for part of its upper boundary with an access road in the upper reaches; and A06, the least disturbed and wooded, had an old gravel road on the eastern slope and experienced minor disturbance at one ground-water well development site.

Premining ground-water systems were described for the five project watersheds. Geologic cores were obtained from each watershed and observation wells established as previously discussed.

Core-hole and drill-hole information showed that two major perched saturated zones (aquifers) underlay each watershed. Relatively impermeable clay or shale beds that underlie coal seams served as the bases for these aquifers. Generally, water in these two aquifers constituted local flow systems, whereas deeper ground water was part of more regional flow systems. Top-aquifer ground water in each watershed was recharged from precipitation and moved downward to the middle aquifer or laterally toward the coal outcrop; discharge was by spring flow or seeps, evapotranspiration, and downward leakage through the underclay. The middle aquifer received some recharge directly from precipitation, seepage along the upper coal-clay-outcrop, and from leakage through the clay supporting the top aquifer. Discharge was mostly as stream base flow, evapotranspiration, or downward leakage to the deep aquifer. Underflow across watershed boundaries occurred in the deep aquifers and in parts of the perched aquifers at M09 and A06. Ground-water levels, spring flow, and streamflow followed seasonal trends in precipitation. However, direct response to rainfall or snowmelt was not evident because of the time needed for percolation through unsaturated zones.

Analyses of aquifer tests at M09 and A06 indicated hydraulic conductivity values of about 10^{-8} to 10^{-6} ft/sec. Using pumping test data, type-curve analyses, and computer simulations yielded similar values of hydraulic conductivity. Best computer simulations were obtained by using values of specific yield in the range of 0.12 to 0.17.

Ground-water quality varied considerably between and within watersheds. Much of the shallow ground water was of the calcium bicarbonate type; deeper water was of diverse water types and was generally more mineralized. Although dissolved-solids concentration was commonly 200 to 600 mg/l, brackish or salty water occurred in parts of the middle and deep aquifers of M09 and A06. Hardness of most ground water was 150 to 300 mg/l and pH was 6.5 to 8.0.

The modeling effort was directed toward watershed hydrology without water quality components. Water quality will be incorporated at a later date. The model will consist of several separate component models which will be linked together to provide a composite model for simulation of surface and subsurface hydrology. The component models will consist of a ground-water model, an unsaturated flow model, an overland flow model, and an evapotranspiration model.

The ground-water model was structured on a grid network and the unsaturated zone was divided into overlying prismatic elements for numerical solution. The unsaturated water movement in each such element was considered to be one-dimensional in the vertical direction. Lateral movement was restricted to surface and ground-water flows.

An unsaturated flow model was formulated and the computer program written. This model is operational on a stand-alone basis. It includes provision for evapotranspiration, and is capable of emulating vertical, one-dimensional water movement in individual prismatic elements.

An available distributed kinematic overland flow model is being used to simulate surface flow.

A modified U. S. Geological Survey ground-water flow model was used to simulate flow in these multi-aquifer watersheds. The model is quasi-three-dimensional in that vertical flow is simulated between aquifers and ground-water flow within an aquifer treated as two-dimensional. Input to each simulation included: ground-water recharge rate, aquifer hydraulic conductivity, confining bed leakance, and stream and spring coefficients.

In these initial ground-water modeling efforts, an instantaneous state was selected for simulation because of its simplicity, and a recharge rate thought necessary to maintain that state was incorporated. Small errors in estimated recharge resulted in simulation of accurate potentiometric surfaces when confining bed leakance was adjusted.

A model with the same constant parameters for top and middle hydrologic units generated good simulations of C06 ground-water levels, except in the eastern part of the top aquifer. In that area, a higher top confining bed leakance could bring that simulated potentiometric surface into better agreement with field observations. For M09, an accurate simulation of observed water levels was achieved with a top aquifer hydraulic conductivity of 2×10^{-7} ft/sec or less, and with an areal variation in the top confining bed leakance.

An analysis was made of one of the costs of reclaiming coal mine, the legal and administrative costs of complying with legislation.

The Ohio stripmine laws were reviewed and found to be among the most demanding state reclamation laws in the nation. The requirements of the Federal Surface Mining Control and Reclamation Act of 1977 were examined and found to be very similar to those of the Ohio stripmine laws. In some cases the Federal Act is more restrictive, but the legal and administrative costs borne by coal companies under the Ohio law are thought to be a surrogate for these costs under the new Federal Act.

A survey of Ohio surface mine operators was used to collect legal and administrative cost data. Regression analysis was used to relate legal and administrative costs to acres in the permit and the tonnage of coal produced.

Results indicate legal and administrative requirements may cost the smaller operator as much as $500 per permit-acre and $0.36 per ton of coal. Larger operators may incur costs of $100 per permit-acre and $0.01 per ton.

A portion of these costs were fees paid to the Ohio Department of Natural Resources, Division of Reclamation, for administration of the state reclamation law, and fees paid to the Ohio Environmental Protection Agency. Generally, these fees covered rule making, monitoring, and enforcement expenses by the state government.

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I. INTRODUCTION

A. Background

Energy demands in the future will probably exceed the available energy supplied by oil and natural gas which will necessitate an increase in the production of coal. Much of this increased demand is likely to be satisfied by increased production of coal from surface mining. As a consequence, there will be an increased need for environmental and economic information on mining and reclamation. In Appalachia, land disturbed by surface mining, to obtain coal for electric power production and other uses, can have profound effects in, and downstream of, an affected watershed, on runoff, erosion, and water quality.

Strip mining may affect the hydrology of surface mined areas by altering runoff rates, erosion, and sediment transport. Barren spoil and applied topsoil material may have decreased infiltration rates, thereby increasing flow rates of runoff from mined areas. Such increased runoff erodes the areas and impedes reclamation while carrying soil particles that cause sedimentation of waterways and reservoirs. Until such areas become stabilized with vegetation, the erosion and sedimentation processes will continue.

A wide range of new hydrologic information is required to assess the erosion and sedimentation potential for different materials and vegetative covers, the design of sediment dams, and the soil water flux to estimate the acidity of drainage water. In addition, the effects of surface mining on the hydrologic regime need to be established for a full determination of the quantity and quality of runoff from watersheds before, during, and after mining.

Numerous studies have been conducted on the reclamation of surface mine spoils by revegetation, and other studies have investigated the chemical and physical properties of spoils to identify the spoil materials which may cause environmental damage. Information is being obtained for developing guidelines for the selection and placement of spoil materials on the basis of their physical and chemical properties to insure optimum vegetative cover and to minimize acid production. Little information, however, is available to meet the pressing need to determine acceptable slopes and slope lengths to minimize erosion.

The establishment of vegetation on spoils in the Appalachian Region is the most difficult where pyritic materials have been placed on or near the surface. Due to oxidation of sulfur, the acid and salts are released which in turn increase the acidity of the mine soil. In addition to high acidity, many spoil banks are low in fertility, have low water holding capacity, and contain toxic amounts of manganese and aluminum. These factors help to create barren spoil banks incapable of supporting plant life. Through a chemical and physical evaluation of the strata obtained by core drilling the most undesirable materials can be identified and covered during the mining operation, thus avoiding the creation of a toxic spoil bank. Federal laws now require soil to be stockpiled and reapplied on the surface of the spoil bank. An evaluation of this requirement needs to be made from the hydrologic, soil erosion, and plant establishment and growth standpoints.

The aforementioned problems can be studied by establishing mathematical relationships of the separate and definable chemical and physical processes and, with the aid of computers, an evaluation can be made of the inter-relationships under given boundary conditions. In such a computer model, the hydrologic behavior could be structured on physically based hydrologic concepts; the erosion and sediment yield subsystems could be defined in terms of surface materials, slopes, cover, precipitation, and surface runoff; and the generation of acid water drainage on pyrite oxidation kinetics and oxidation product removal. Such a computer model to simulate the dynamic soil-water-chemical system could be useful in predicting spoil placement, reclamation treatments, runoff and sediment yield, and acid water drainage for the minimization of environmental pollution under economic constraints.

Models are essential to understanding and predicting the transport of water, sediment, and chemicals through a watershed system. In the natural environment, a watershed offers an appropriate element for modeling because all controlled surface water exits through the stream channel.

Studies have been conducted to describe various conditions of different watersheds with models. Existing models can be evaluated as to their applicability in developing a model for the study of watersheds for both pre- and post-surface mined conditions.

A description of the hydrogeology of watersheds and the water quality characteristics of the aquifer systems for pre- and post-surface mining conditions is needed. A ground-water model can be developed or adapted for simulation of the ground-water flow conditions and movement of solutes for the pre- and post-surface mining condition.

Costs to obtain the necessary physical, chemical, and hydrologic data, including legal and administrative costs, required for surface mining permits need to be evaluated. The costs for obtaining these data at various degrees of accuracy and completeness and the costs and benefits of alternative degrees of control of runoff, sediment, and water quality should be evaluated. It is essential that the different procedures in reclamation be evaluated as to cost and their effects on the environment.

B. Study Objectives

The motivation for the study was the Federal surface mine legislation passed by the 94th Congress which was later enacted by the 95th Congress as Public Law 95-87, "Surface Mining Control and Reclamation Act of 1977." The Federal Energy Administration and the U. S. Bureau of Mines outlined some basic study needs for obtaining desired hydrologic and water quality data from watershed subjected to surface mining through the three phases: (1) premining, (2) mining, and (3) postmining. Methods or procedures were also desired for use in answering the broader questions of how surface mining influences hydrology and water quality, and what would be the economic and environmental impacts of a more comprehensive regulation of surface mining and reclamation.

The study, sponsored by the U. S. Bureau of Mines, for reaching these overall goals involved a joint effort by the USDA-SEA-AR, North Appalachian Experimental Watershed, Coshocton, Ohio, and the Ohio Agricultural Research and Development Center (OARDC), Wooster, Ohio, in cooperation with the U. S. Geological Survey (USGS), the Soil Conservation Service (SCS), the Utah State University (USU), the Muskingum Watershed Conservancy District, and three private coal mining companies.

The specific objectives of the study were divided into tasks for which the USDA-SEA-AR and the OARDC were responsible, with designated contributions for tasks undertaken by the USGS, SCS, and USU under reimburseable cooperative agreements. These objectives and tasks are as follows:

> Objective 1: Obtain and analyze hydrologic and water quality data from a control watershed; from four other watersheds (30 to 50 acres in size) before, during, and after surface mining of different coal seams; and from erosion and treatment plots.
>
> Tasks:
>
> 1. Install flumes and water samplers at outlet of each study watershed; weirs to measure spring flows; soil moisture access tubes; and weather instruments (USDA).
> 2. Install weirs and water samplers on sediment ponds, and water measuring and sampling equipment on erosion and treatment plots (USDA).
> 3. Reinstall flumes, water samplers, and soil moisture access tubes following surface mining (USDA).
> 4. Obtain water flow measurements and collect water and sediment samples (USDA-OARDC), and analyze samples (OARDC).

5. Apply reclamation treatments to treatment plots, and collect runoff samples and plot data (OARDC).

6. Evaluate the available data relative to runoff, erosion, water quality, and reclamation (USDA-OARDC).

Objective 2: Characterize the study watershed and plots, and obtain physical and chemical data for the soils and overburden materials before surface mining and for the replaced topsoil and underlying spoil material after surface mining.

Tasks:

1. Map and characterize soils on study watersheds (SCS-OARDC).

2. Collect samples and conduct analyses of physical and chemical properties of soil materials (OARDC).

3. Obtain geologic cores from study watersheds (USGS).

4. Determine chemical and physical parameters on geologic cores (OARDC).

5. Map the reconstituted soils on reclaimed study watersheds (SCS).

6. Collect samples and conduct analyses of chemical and physical properties of the reconstituted soils and underlying spoil materials (OARDC).

7. Measure water infiltration and percolation characteristics of the undisturbed and reclaimed watershed soils (USDA-SCS-OARDC).

Objective 3: Describe the hydrogeology of the watersheds and the water-quality characteristics of the aquifer systems for pre- and post-surface mining conditions, and develop or adapt a ground-water model for simulation of the ground-water flow conditions and movement of solutes for the pre- and post-surface mining conditions.

Tasks:

1. Obtain geologic cores for stratigraphic correlation and chemical and mineralogical analyses of stratigraphic units (USGS).

2. Drill observation wells and install water-level recorders (OARDC-USGS).

3. Collect water level, water quality, geophysical, and aquifer characteristic data (USGS).

4. Describe the hydrogeologic system, develop conceptual models of ground-water flow and solute-transport systems, and develop or adapt digital computer models to simulate ground-water flow (USGS).

5. Reinstall observation wells that are destroyed during mining phase (OARDC-USGS).

6. Adjust ground-water model for simulation of postmining conditions (USGS).

7. Prepare required reports (USGS).

Objective 4: Develop or modify a computer model to simulate the hydrologic and water-quality regimes of the study watersheds for both pre- and post-surface mined conditions, by incorporating mathematical representations of separate models for the water flow components and sediment and chemical transport, with emphasis on selection of model parameters that can be reasonably acquired for non-study areas within the physiographic region for application of the model.

Tasks:

1. Develop or modify a computer model for simulation of watershed hydrologic and water quality components for premining conditions (USDA).

2. Modify or adjust a computer model for simulation of postmining conditions of runoff, sediment yield and water quality with incorporation of a ground-water model as developed under Objective 3 (USDA).

3. Utilize the watershed model to simulate the response of the study watersheds over a full range of climatological conditions and for different reclamation treatments (USDA).

Objective 5: Determine costs to obtain the necessary physical, chemical, and hydrological data, including legal and administrative costs, as required for surface mining permits as well as costs for obtaining these data at alternative degrees of accuracy and completeness; and determine costs and benefits of alternative degrees of control of runoff, sediment, and water quality.

Tasks:

1. Estimate legal and administrative costs of obtaining necessary data required to obtain mining permits (OARDC).

2. Estimate relationship between reclamation costs and alternative degrees of control of erosion, sedimentation, and runoff (OARDC).

3. Estimate benefits received under an alternative method of water pollution control (OARDC).

4. Evaluate alternative water pollution control rules in terms of results and costs (OARDC).

C. Literature Review

1. Surface-Water Hydrology

Much of the literature on hydrologic studies associated with mining deals with the evaluation of acid mine drainage from both deep and surface mines. In some cases the hydrology and water quality conditions of unmined watersheds were monitored.

Surface-water hydrology is influenced by various parameters such as rainfall intensity and amount, soil properties and moisture status, topography, type and amount of soil cover, etc. (Pennington, 1975). Most of the mining areas in the Appalachian Region are located in hilly terrain and subject to relatively high rates of runoff before mining. Collier et al. (1970) reported that nearly 48 percent of the annual precipitation (117 cm, 46.1 in.) in Southeastern Kentucky ran off from basins having drainage areas of 388 sq. km (150 sq. mi.) or less. It was found that from January through March the total runoff was approximately 30 cm (12 in.). The runoff was highest (11.4 cm, 4.5 in.) in February and lowest runoff, averaging between 0.25 cm (.10 in.) and 0.51 cm (.20 in.), was observed in October. In dry years, however, they found no measurable runoff during September, October, or November. In Eastern Pennsylvania, with an average annual precipitation of approximately 109 cm (43 in.), the infiltration and surface runoff were approximately 27 cm (11 in.) each in unmined watersheds (Pennington, 1975).

McGuinness and Edwards (1975) reported runoff data from two soils in Ohio; namely, Keene (moderately well-drained, slowly permeable) and Rayne (well-drained, moderately permeable) under a four-year rotation (corn, wheat, meadow, and meadow) for the period 1945-1968. During the growing season the average monthly runoff was 1.1 cm (.43 in.) and 0.48 cm (0.19 in.) for Keene and Rayne soils, respectively. During the dormant season the average monthly runoff for the Keene soil averaged 4.2 cm (1.7 in.) of runoff compared with 1.0 cm (.39 in.) for Rayne.

In Ohio, the sandy soils have a capacity to retain approximately 2.54 cm (1.00 in.) of water and the clays approximately 10 cm (3.9 in.) per 30 cm (12 in.) of soil (Agronomy Guide, 1977).

Curtis (1977) reported that soils on a forested watershed in Southeastern Kentucky are relatively thin, generally from 0.3 m (1 ft.) to 0.9 m (3 ft.) thick and have a water retention ranging from 7.6 cm (3.0 in.) to 25.4 cm (10 in.).

The U. S. Soil Conservation Service (1969) has developed procedures for predicting runoff from precipitation, potential storage as adjusted for soil cover and land use, and infiltration rates for a wet soil profile. The latter factor is incorporated by assigning soils into four hydrologic groups; i.e., A, B, C, and D. Group A refers to soils which are typically coarse, deep sands having high rates of infiltration and internal water movement. Soils in Group D are mostly clay having high swelling characteristics with low rates of infiltration and internal water movement. Shallow soils that have nearly impermeable subhorizons belong to the D group. Soils in Groups B and C have characteristics intermediate between Groups A and D. In a study conducted in Southeastern Kentucky on three watersheds, approximately one-third of the soils were in Group B and two-thirds in Group C (Musser, 1963).

2. Surface-Water Quality

Surface-water quality may be affected by soil type, topography, intensity and duration of rainfall, and vegetative cover. For Southeastern Ohio, Youngquist (1959) reported that there is a natural range in dissolved and suspended solids which results largely from the manner and time it takes precipitation to reach the streams. All natural waters contain dissolved mineral matter composed principally of silica, iron, manganese, calcium, sodium, potassium, bicarbonate, sulfate, chloride, fluoride, and nitrate. Generally the quantity of dissolved matter in the water depends on solubility of minerals (present in rocks and soils) in the drainage basin (Youngquist, 1959).

During rainy periods, and when snow-melt runoff reaches the stream, the quantity of dissolved salts in the water can be relatively small, and the quantity of suspended solids is usually relatively large because of high flow rates. During dry periods when a large proportion of the water travels at a low velocity through stream channels, (the source of the water being ground water), the concentrations of dissolved salts are ordinarily much higher and of the suspended solids much lower.

Studies have been conducted to determine surface-water quality for unmined watersheds in Eastern Kentucky for use as a reference for mined watersheds (Dyer and Curtis, 1977; Collier et al., 1970).

Collier et al. (1964) studied the stream water quality from a forested watershed in Southeastern Kentucky and found that generally the concentration of dissolved solids was less than 30 ppm and the pH of water ranged from 5.0 to 7.2. The principal ions found in the water were calcium, magnesium, bicarbonate, and sulfate. Silica accounted for about 25 percent of the total dissolved solids of the stream. Also, another study conducted in Southeastern Kentucky to determine the effect of mining on water quality has been reported on by Curtis (1972a, 1972b, 1973, 1974) and Dyer and Curtis (1977). The means of water quality and discharge values for an unmined watershed from 1968-1975, reported by Dyer and Curtis (1977), were as follows: discharge 61.2 cm (24.1 in.), turbidity (T.U.) 19, conductivity (micromhos/cm) 77, pH 6.8, sulfate (ppm) 15, chloride (ppm) 3.3, bicarbonate (ppm) 17, calcium (ppm) 5.3, magnesium (ppm) 3.0, sodium (ppm) 2.7, potassium (ppm) 1.8, iron (ppm) 0.1, aluminum (ppm) 0.04, manganese (ppm) 0.006, and zinc (ppm) 0.01. These elements occur in rocks and soils and most are found in low concentrations in surface waters that have not been polluted with wastes from municipal or industrial areas (Hubble and Collier, 1960).

3. Ground-Water Hydrology

The influence of coal mining on the quantity and quality of ground water for domestic use in rural areas is of considerable interest.

Musser (1963) reported that in most of the eastern coal fields the boundaries of the ground-water drainage are approximately the same as the boundaries of the surface drainage. The slight dip of the beds and the orientation of fractures cause some variations in ground-water drainage, but these variations are probably small. The slow movement of water at great depth is independent of the topography and probably is not significantly affected by surface mining.

Brown and Parizek (1971) found that three separate water tables were present within the rocks associated with deep mines developed in the lower Kittanning "B" coal of the Allegheny Series in the Kylertown, Pennsylvania, area. The uppermost water table was within sandstones, siltstones, and shales above the coal, with a maximum thickness of approximately 30.5 m (100 ft.). The second water table was associated with the mined-out coal seam. The third water table was within the more massive and extensive sandstone of the Pottsville series. Parizek and Tarr (1972) reported that a similar hydrogeologic setting involving two or more distinct water tables occurs in many other mining regions.

According to Musser (1963) shallow ground water moves from topographically high areas to discharge into streams as is normal in humid regions. Generally, the recharge occurs in the higher areas and discharges occur in the lower areas (Herring, 1977).

Hollyday and McKenzie (1973) found that in hilly terrains precipitation that enters the upper and middle part of each hill, moves vertically down through the soil and rock, moves horizontally through fractured sandstones, and then is discharged from the aquifers. Some of the water moves deeper into the underlying rock formations to recharge the deeper part of the ground-water flow system, then moves longer distances horizontally under the hills and small upland streams, and finally moves upward to be discharged into major streams.

The quantities of water available from the ground-water system by wells will depend upon the hydraulic properties of the aquifer (Carswell and Bennett, 1963). In Southwestern Ohio, large supplies of water are available to wells only from the unconsolidated deposits of sand and gravel in the major river valleys (Youngquist, 1959). The bedrock beneath most of the area consists of alternating sandstones and shales with some limestone. Where thick porous sandstones are present, more water is available than where bedrock is predominately shale. In Western Pennsylvania, Carswell and Bennett (1963) found sandstones of the Pennsylvanian and Mississippian ages to be generally much higher in both lateral and vertical permeability than shales of these ages.

The coefficient of permeability, which is a measure of the capacity of the medium to transmit fluid, depends on both lateral and vertical permeability. Tests conducted in Western Pennsylvania indicated the permeability of sandstone ranged from 370 liters (9.08 gal.) to 1,439 liters per day per square meter (35.3 gal. per day per ft.^{2}) (Carswell and Bennett, 1963). They concluded that the Homewood sandstone member of the Weshannock quadrangle with a thickness of 6.1 meters (20 ft.) to 12.2 meters (40 ft.) had a transmissivity range of about 2,466 liters (200 gal.) to 17,266 liters per day per meter (1,390 gal. per day per ft.). Herring (1977) reported that permeabilities in the Eastern Interior Coal Province ranged from 41 liters (1.0 gal.) to 1,019 liters per day per square meter (25 gal. per day per ft.^{2}). This area is located in Illinois, Indiana, and Western Kentucky where the bedrock consists predominately of shale, sandy shale, and sandstone with minor amounts of limestone.

4. Ground-Water Quality

The pollution of ground-water supplies is a major concern because of the time and difficulties involved in restoring the original water quality. Acid mine drainage from coal mining may pollute underlying aquifers through joints, fractures, and abandoned oil and gas wells. In Arkansas, oil well drillings resulted in deep water aquifers being polluted. After the oil wells were plugged to stop the source of pollution, it was estimated that it will take 250 years for a complete restoration of the original water quality (Emrich and Meritt, 1969).

As was mentioned before, generally, the quantity of dissolved solids in the ground water depends upon the solubility of minerals in the drainage basins. In the coal basins of Western Maryland, Hollyday and McKenzie (1973), found that water unaffected by mine drainage from six wells ranging in depth from 13.7 meters (44.9 ft.) to 152.4 meters (500.0 ft.) had dissolved-solids concentrations ranging from 35 to 305 mg/l, with a median of 170 mg/l. Calcium concentrations ranged from 6.0 to 75 mg/l, magnesium 2.3 to 15 mg/l, and bicarbonate 27 to 292 mg/l. Although the wells were open to one or more coal seams, the concentration of iron did not exceed 0.8 mg/l and the sulfate did not exceed 45 mg/l.

Pietz et al. (1974) established wells in Fulton County, Illinois, to monitor ground-water quality in undisturbed and mined areas. The area is located in a Pennsylvanian age formation consisting mainly of Canton shale with thin sandstone, limestone, and coal beds (Bergstrom, 1956). For the undisturbed area the means and frequencies of detection for the selected chemical parameters were: Total P (14 mg/l, 86.4%), Cl (11.9 mg/l, 99.3%), $SO_4^=$ (127 mg/l, 96.6%), Kjeldahl N (1.22 mg/l, 80.8%), NH_3-N (1.04 mg/l, 94.6%), $NO_2 + NO_3$ - N (0.82 mg/l, 68.5%), K (1.5 mg/l, 97.9%), Na (30.4 mg/l, 100%), Ca (103.2 mg/l, 100%), Mg (56.8 mg/l, 100%), Zn (8.2 mg/l, 100%), Cd (0.000 mg/l, 10%), Cu (0.04 mg/l, 67.8%), Cr (0.003 mg/l, 20.1%), Ni (0.02 mg/l, 14.2%), Mn (0.86 mg/l, 100%), Pb (0.08 mg/l, 70.5%), Fe (18.3 mg/l, 100%), Al (0.8 mg/l, 54.7%), and Hg (0.17 mg/l, 53.0%).

In a coal mining area of Western Pennsylvania, Caruccio (1968) measured the calcium and sulfate levels in water samples from wells. The calcium concentrations of the water ranged from 0 to 38 mg/l and the sulfate ranged from 0 to 72 mg/l.

In the Eastern Interior Coal Province, Herring (1977) found that the dissolved-solids concentrations of ground water obtained from shallow aquifers ranged from 50 to 250 mg/l in the unglaciated, hilly areas and from 150 to 400 mg/l for the glaciated areas. The deep aquifers may contain a sodium-bicarbonate or sodium-chloride type water. Total dissolved solids in the ground water from the Lisman Formation was approximately 325 mg/l for an undisturbed area near Central City, Kentucky (Herring, 1977).

5. Approaches to Watershed Modeling

Water transport in a watershed system can be described by considering the porous medium as a continuum and utilizing the partial differential equations representing three-dimensional saturated-unsaturated flow coupled with equations of unsteady free-surface flow as presented by Freeze (1972a, 1972b). The movement of chemicals through porous media by water and the chemical reactions that occur during movement can also be described by partial differential equations as reviewed by Boost (1973). The partial differential equations involved can be solved by finite difference techniques. Similar applications can be made to the unsteady flow of water (Reddell and Sunada, 1970) and to the transport of dissolved substances by unsteady, free-surface flow (Bella and Dobbins, 1968; Dresnack and Dobbins, 1968; and Harleman et al., 1968).

The major portion of the precipitation falling on a watershed is lost back to the atmosphere by the processes of evaporation and transpiration (evapotranspiration) and this important water-flow component must be included in any continuous hydrologic model. An energy balance-resistance approach (Hamon and Belt, 1973), appears to have merit for watershed predictions of evapotranspiration and requires estimates of solar radiation, wind, temperature, humidity, surface roughness, and a relative surface resistance term which is dependent on the vegetative cover and the available soil water.

On a watershed scale, simplification of mathematical models for describing the transport of water, sediment, and chemicals for any practical application must be made. Such is the case when the nonlinear equations are linearized (Dooge and Harley, 1967); when the kinematic approximations of surface flow equations are made (Woolhiser and Liggett, 1967); and when molecular diffusion and hydrodynamic dispersion in transport of chemicals through porous media are neglected (Nelson and Eliason, 1966).

Models that have experienced practical application are of the lumped or compartment form and rely on parameters for simulation of hydrologic processes, such as the Stanford Model (Crawford and Linsley, 1962) and the Hydrograph Laboratory Model (Holtan et al, 1971). The Stanford Model has been applied to agricultural watersheds in Ohio (Ricca, 1972) and modified to accommodate multiple ground-water recession constants for basins with a stratified geology. Peck (1966) describes the lumped continuous simulation model used by the National Weather Service. This model was developed for forecasting purposes. It simulates all the major components of watershed hydrology. The model was developed so that each parameter had a physical interpretation for which bounds could be established. Parameter optimization is required but, based on experiences and because of the physical interpretation of the parameters, reasonable initial values are possible allowing quicker convergence to a final set of parameters. Shanholtz and Lillard (1971) modified the Stanford Watershed Model to study the hydrology on agricultural watersheds. The problems of using lumped and calibration type models became apparent in their simulation work; the final set of calibrated parameters depended on the time interval of the recorded flows used, and the components considered important for simulation.

In contrast to the lump type models, distributed models describing the spatial variability of surficial features have been developed. Holtan et al (1975) developed the USDAHL Model (U. S. Department of Agriculture Hydrograph Laboratory Model), which is a distributed continuous simulation hydrology model. This model uses zones, or hydrologic response units, as hydrologically homogeneous areas over which infiltration and evapotranspiration are averaged to describe the hydrologic system. Also, the soil profile in each zone is separated into layers. The surface water from each zone cascades to the more downstream zones. Some empirical relations between measurable parameters and hydrologic processes were combined in the overall model. The USDAHL Model has been used to simulate water yield and to assess the hydrologic effects of land-use change on a 40-acre watershed in Ohio associated with the Middle Kittanning (No. 6) Coal (Langford and McGuinness, 1976). Onstad and Brakensiek (1968) developed a distributed event-based hydrology model using the stream tube concept. A stream tube is part of a flow net delineated by a pair of lines perpendicular to contour lines, wherein the flow is assumed to be confined. Flow is treated as lateral inflow into the stream channel. Gupta and Solomon

(1977), Solomon and Gupta (1977), and Gupta and Solomon (1977) describe in their series of papers a distributed watershed model using a surface grid approach. Their model was developed to use fundamental relationships which require only readily available data. All components of the hydrologic cycle were modeled including ground water. Knapp et al (1975) developed a distributed continuous hydrologic model which simulated the different components of the hydrologic cycle including the ground-water piezometric surface. The area was divided into homogeneous grid units of one square mile for the ground-water component. Larger blocks of area were considered for the surface where flow was assumed to occur in the stream channels rather than as overland flow. Huggins et al (1977) developed a distributed parameter, event-based model for use as a planning tool. The model essentially simulates overland flow and does not consider ground-water flow or storage. Grids represent the surface of the watershed. Erosion and subsurface drainage models have also been coupled with this surface model.

The erosion process (detachment, transport, and deposition of soil particles) has been modeled (Meyer and Wischmeier, 1969; Meyer, 1971) but practical solutions for erosion and sediment yield predictions, at present, rely on empirical approaches (Wischmeier and Smith, 1979; Wischmeier and Mannering, 1969; Wischmeier et al, 1971; and Williams and Berndt, 1972). A mathematical watershed sediment model has been presented by Onstad (1973).

6. Economics

Surface mining presents a classic case of the "externality" problem. Briefly, the externality problem is present when all the costs or all the benefits of a process are not internalized by the producer or consumer. In the case of surface mining, the coal mine production process of the operator may create an unsightly landscape and water pollution problems. Only a small portion of the costs of the marred landscape is borne by the producer. Most of these monetary and aesthetic costs must be borne by others in the community. Similarly, the costs of water pollution are not borne by the producer but by the downstream user.

Society has determined that these externalities must be lessened. State legislatures and the U. S. Congress have enacted laws which require producers to reclaim surface mine lands and control pollution. A collective decision has been made to lessen the external costs and to force producers to bear the involved costs.

The objective of economic research is to help decision makers analyze problems. This analysis commonly is done by evaluating the benefits and costs of alternative courses of action. The problem of externalities from surface mining is analyzed by viewing the benefits and costs of reclamation. Society enjoys obvious benefits from reclamation such as improved aesthetics, improved productivity from the reclaimed land, economic growth potential in the community surrounding surface mines, improved water quality, and so forth. But society must also bear costs to reclaim land. Eventually, the reclamation costs borne by the producer is reflected in the price of coal and consumers pay the costs.

Thus, the questions typically posed by economic research are:

1. What are the societal benefits of reclamation?

2. What are the societal costs of reclamation?

3. Who benefits and who bears the costs?

In surveying the literature, little work has been done to answer the first question, substantial effort has been involved in answering the second, and few research projects have addressed the third.

Those studies addressing all three questions include Randall et al (1977) and Stinson and Voelker (1978). Randall (1977) estimated the benefits and costs of reclamation in a case study region of Central Appalachia. Results showed that reclamation benefits exceeded costs under Kentucky reclamation laws. To meet the reclamation requirements of the 1977 Federal legislation, estimated costs and benefits became nearly equal. This study is one of the few that analyzed both benefits and costs. However, the small area used in the analysis makes extrapolation to other areas difficult. Stinson and Voelker (1978) estimated some of the indirect benefits and costs and also addressed the distribution of these benefits and costs. Their analysis measured the state and local taxes generated by coal mines in four western states. Also, they evaluated the new demands for state and local services created by the development of the Northern Great Plains coal reserves.

The vast proportion of the literature consits of cost studies. The results of these studies are estimates of (a) the costs of reclamation and/or, (b) the legal and administrative costs of complying with reclamation regulations.

Baker (1973) developed information for the Appalachian Regional Commission to project pollution control costs in the Monongahela River Basin. Also, this research sought to provide an effective, workable handbook for estimating pollution control costs and the factors affecting these costs.

Another study in the Appalachian region used an economic engineering approach to simulate reclamation costs on 42 hypothetical mines (Nephew and Spore, 1976). These hypothetical mines are thought to be typical of those found in Appalachia. A model was developed relating costs of reclamation to (a) quality of reclamation obtained, (b) slope of the original landscape, and (c) the overburden to coal stripping ratio.

Another approach to estimating reclamation costs in Appalachia is found in Evans and Bitler (1975). Here, reclamation data were obtained through on-site inspection and interviews for 20 coal surface mining operations. Reclamation costs were divided into three categories: premining planning, backfilling, and revegetation.

A host of studies report reclamation costs for "representative" surface mines in Appalachia or a few Appalachian mines that are thought to be typical of the industry. U. S. EPA (1974) found the costs of reclamation for a typical surface mine in Eastern Kentucky to be about 8 percent of total production costs. Katell et al (1976) used 3 coal strip mines to estimate typical capital investments, operating costs, and prices received for coal. Curry (1977) reported that the back-to-contour reclamation increased costs $2.40 to $2.93 per ton of coal in the mountainous area of Tennessee.

Several studies investigated the costs of reclamation in western states. Persee et al (1977) used data from 13 mines in 9 states west of the Mississippi River to estimate reclamation costs. This study divided costs into design and engineering costs, bonding and permit fees, backfilling and grading costs, and revegetation costs. Leathers (1977) presented a comprehensive study of several sites in the West. First, local, state, and Federal reclamation laws were outlined. Then reclamation costs were derived using an activity analysis approach and a standard engineering cost analysis. Results indicated that earth handling (recontouring and topsoiling) accounted for about 70 to 80 percent of all reclamation costs. Costs averaged $3,500 per acre or about $.05 per ton. Anothern western study (Bailey, 1973) projected that reclamation costs range from $.02 to $.20 per ton.

Schottman (1975) reported on an engineering model used to estimate costs for a range of reclamation site characteristics. The simulation model was developed for application in any region within the United States. Estimates were that reclamation on an average site in western regions cost an average of $1.32 per ton. Costs of reclamation for area mining in the Midwest averaged $1.30 per ton, and costs of reclamation for area mining in Appalachia totaled $2.50 per ton.

Another model was reported by Foreman (1974) which assessed the costs of reclamation and can be applied on an area to area basis. The purpose of this mathematical model was to estimate reclamation costs per ton of coal mined for various levels of reclamation on sites with a range of physical characteristics.

A number of studies analyzed the impacts of the 1977 Federal reclamation legislation. Library of Congress (1977) analysts examined the costs of reclamation which would occur to both consumers and producers to meet the standards of the new Federal legislation. Their estimates of incremental costs due to this legislation ranged from $.30 to $.85 per ton of coal depending on the efficiency of the mine. They expected costs to consumers to rise only slightly. Their assessment was that a disequilibrium has developed in energy markets; thus prices of coal no longer accurately reflect costs. They estimated that where prices are not established by costs, reclamation costs are borne by producers and not consumers.

In short, a number of researchers have investigated costs of reclamation, but few have tackled the larger analysis of estimating both benefits and costs. The reason for this omission is obvious since most of the aesthetic and environmental benefits are very difficult to quantify. However, rational economic decisions cannot be made without some notion of the magnitude of the benefits in relation to the magnitude of the costs.

II. DESCRIPTION OF STUDY SITES

A. Introduction

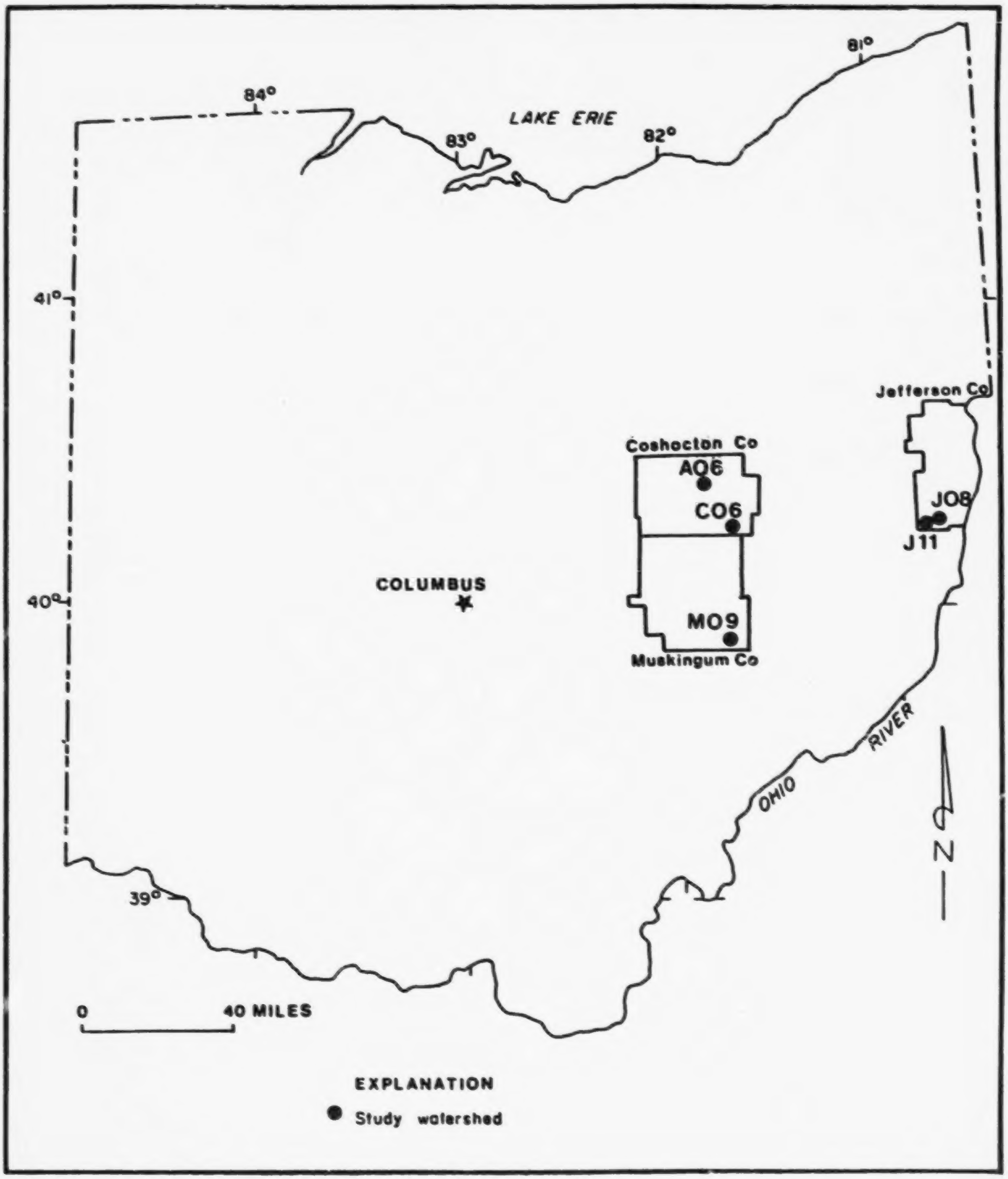
A total of five watersheds, ranging in size from 29 to 49 acres, were selected to study the effects of mining and reclamation on hydrology and water quality. Four of these watersheds will be mined, and one will be left in its natural state and used as a control watershed. All the watersheds were located in east-central Ohio, as shown in Figure 1, and, with one exception, were numbered in accordance with the county and the surface mineable coal seam (Table 1). The study watersheds in Coshocton County (C06 and A06) and the one in Muskingum County (M09) were located in the Muskingum River Basin. The two Jefferson County sites (J11 and J08) drained into small tributaries of the Ohio River.

In selecting study watersheds the following criteria were used:

1. There should be four study watersheds, each having a different coal seam to be mined, representing different geologic and soil profiles.
2. The watersheds should be located in the North Appalachian Region (preferably in Ohio) and be mined by cooperating coal companies within a one- to two-year period after project initiation.
3. Watersheds should have experienced a minimum of prior disturbance and should be vegetated.
4. Each watershed should have at least 75 percent of its area disturbed during mining and reclamation, except for one watershed that has experienced deep mining and where the remaining outcrop coal will be removed by the haul-back mining method.
5. An additional watershed, not to be mined, should be monitored as a control or index area and should have an outcropping coal seam, a record of hydrologic data, and should have been relatively undisturbed for a number of years.

The four watersheds to be mined (C06, M09, J11, and J08), each with a different coal seam, were chosen because the natural and mine-modified geologic profiles would be different, reflecting different ground-water flow regimes, soils, and vegetation--all major factors to consider in overall hydrology of any watershed.

The control watershed (A06) will serve as a hydrologic bench mark to reflect only the natural climatic factors and not the effects



84°
83°
82°
81°
LAKE ERIE
41°
40°
39°
Jefferson Co
Coshocton Co
A06
C06
J08
J11
COLUMBUS
M09
Muskingum Co
OHIO RIVER
N
0
40 MILES
EXPLANATION
● Study watershed

Figure 1. Location of Study Watersheds.

Table 1. Watershed Identification, Location, and Associated Coal

Watershed Identification[1]	County in Ohio	Location in County	Name and No. of Coal Seam
C06	Coshocton	Extreme southeast corner of county, Section 22 of Linton Township	Middle Kittanning, No. 6
M09	Muskingum	Southeast corner of county, Section 17 of Meigs Township	Meigs Creek, No. 9
J11	Jefferson	Extreme southwest corner of county, Section 34 of Mt. Pleasant Township	Waynesburg, No. 11
J08	Jefferson	Extreme southwest corner of county, Sections 12 and 18 of Mt. Pleasant Township	Pittsburgh, No. 8
A06[2]	Coshocton	Central part of county, at USDA-SEA-AR, North Appalachian Experimental Watershed, Section 5 of White Eyes Township	Middle Kittanning, No. 6

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[1] The naming convention for each site has two roots: location and coal seam. The first letter is the first letter of the county in which the study watershed lies, and the last 2 numbers indicate the coal seam that will be mined. The one exception to this convention is Watershed A06 - the control watershed.

[2] Generally identified as Watershed 172 at the North Appalachian Experimental Watershed.

of mining or land treatment. The watershed experienced a partial cutting of trees from 1964 to 1971, but was stable from 1950 to 1963 (Langford and McGuinness, 1976). Operation of the stream gaging station ended in 1972 but was reinstated in July, 1975 for this study. No statistical treatment was made on the effects of persistance of the partial cutting, but it was assumed to be negligible, since only small areas of the watershed were affected. Thus, Watershed A06 can be used as a control area for evaluation of the effects of mining and reclamation on the other study watersheds.

B. Physical Characteristics

Topographic maps for the study watersheds are shown in Figures 2-6 and the legend for symbols on the topographic map is shown in Table 2. Oblique aerial photographs of each site, except A06, are shown in Figures 7-10. The physical characteristics of the watersheds are given in Table 3.

The main watercourse of the M09, J08, and A06 watersheds, in their premined condition, had continuous flow; however, C06 and J11 watersheds were borderline cases between ephemeral and continuous flowing streams. The drainage system in each study watershed consisted of a well defined main channel with one less developed major contributing ephemeral channel, and several poorly developed side channels that contributed only intermittent flows.

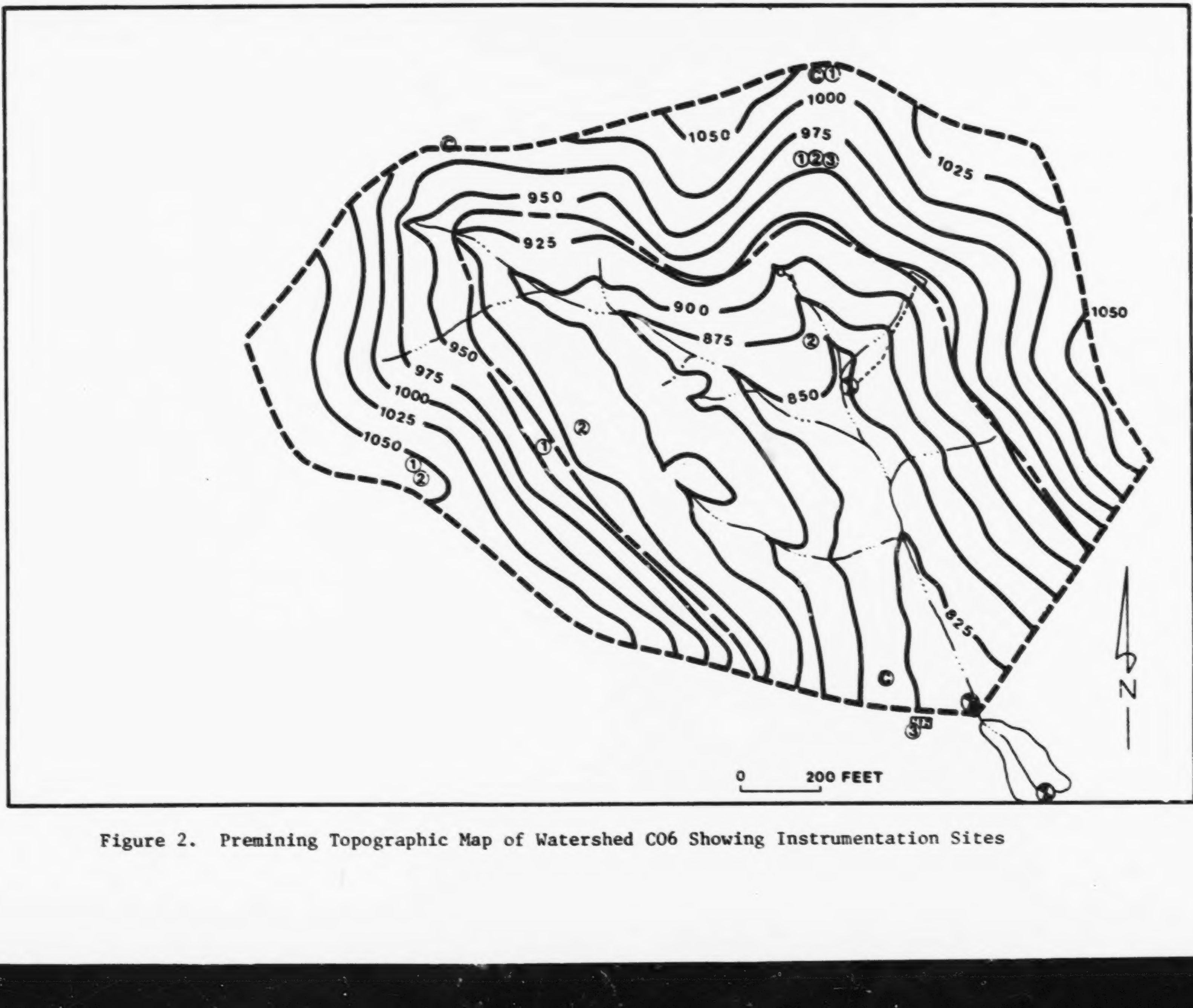
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Figure 2. Premining Topographic Map of Watershed C06 Showing Instrumentation Sites

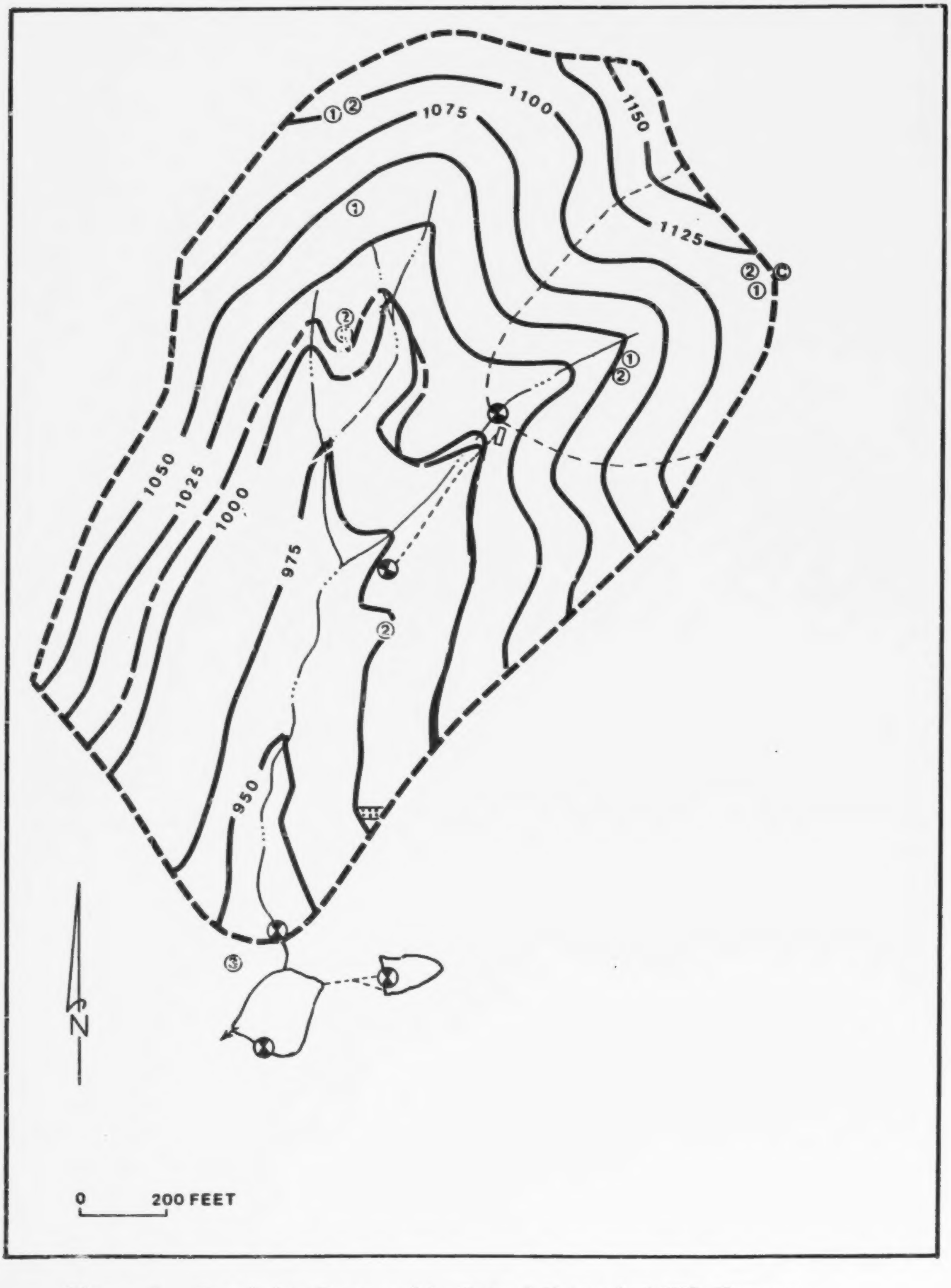
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Figure 3. Premining Topographic Map of Watershed M09 Showing Instrumentation Sites

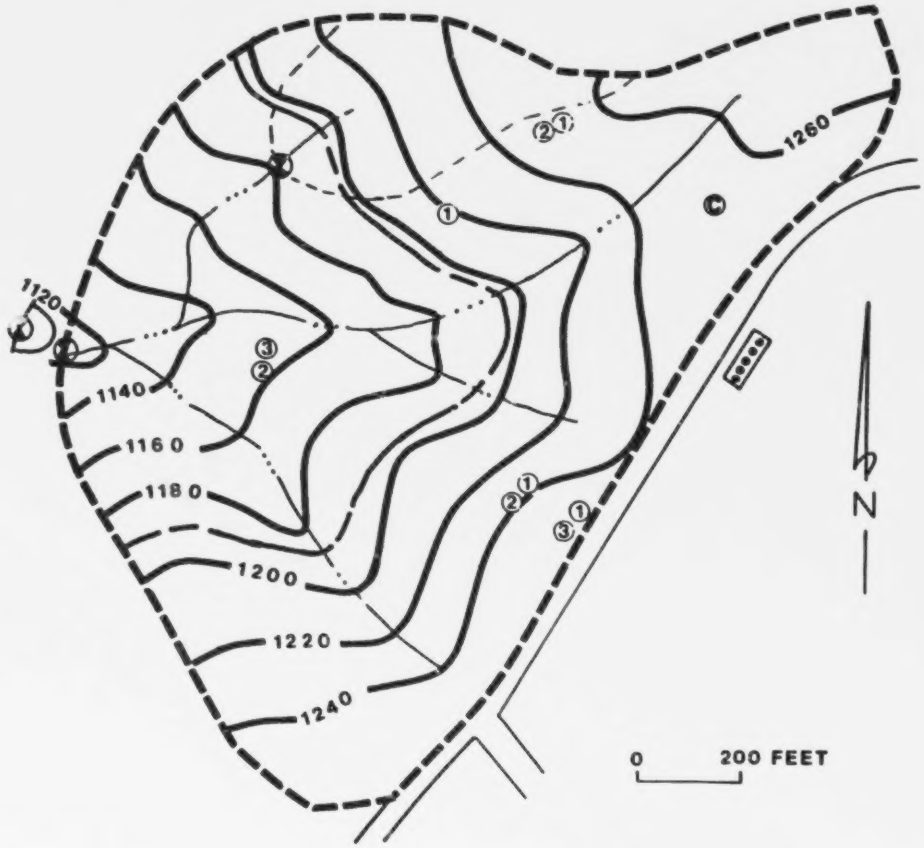
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Figure 4. Premining Topographic Map of Watershed J11 Showing Instrumentation Sites

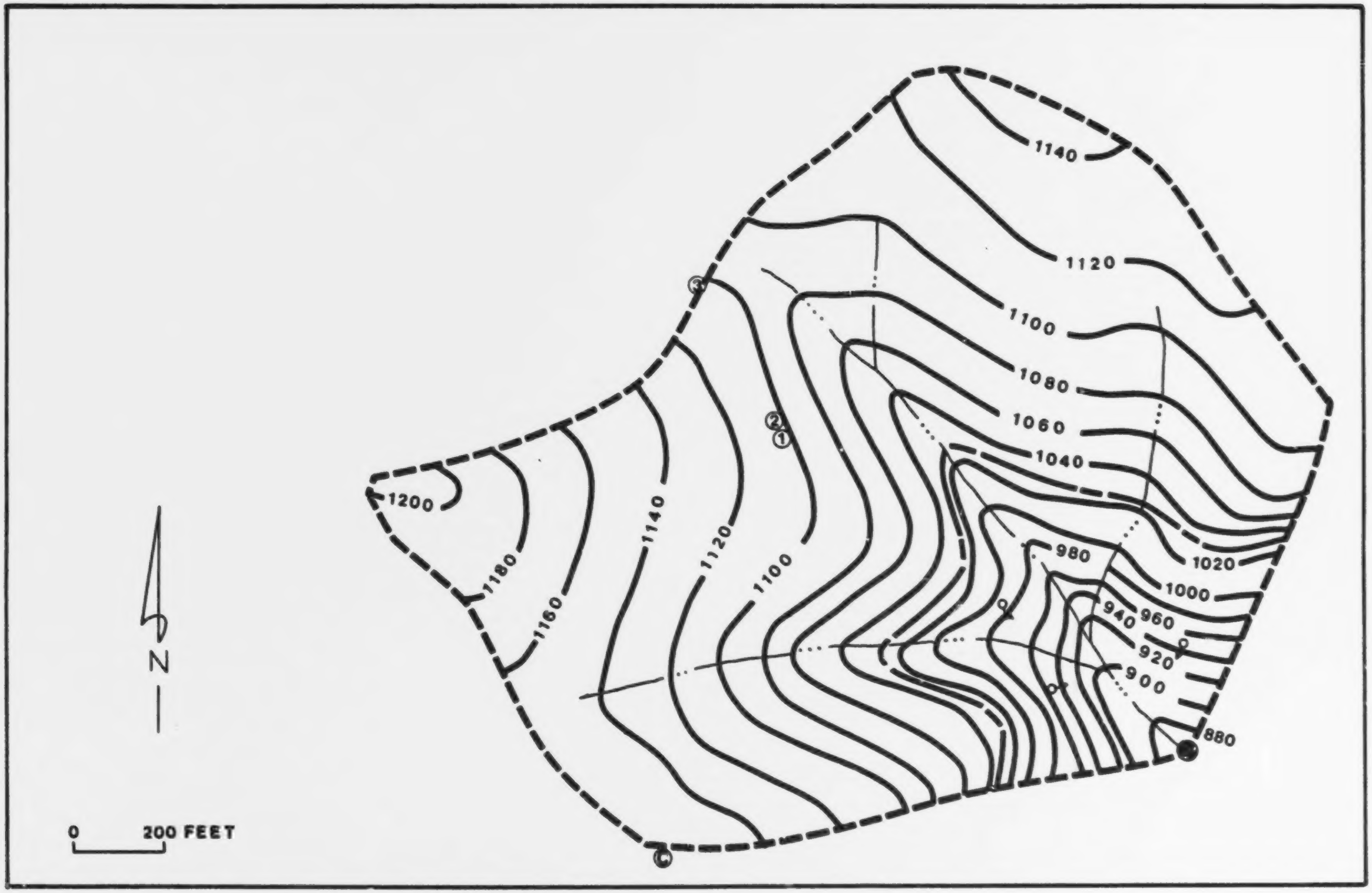
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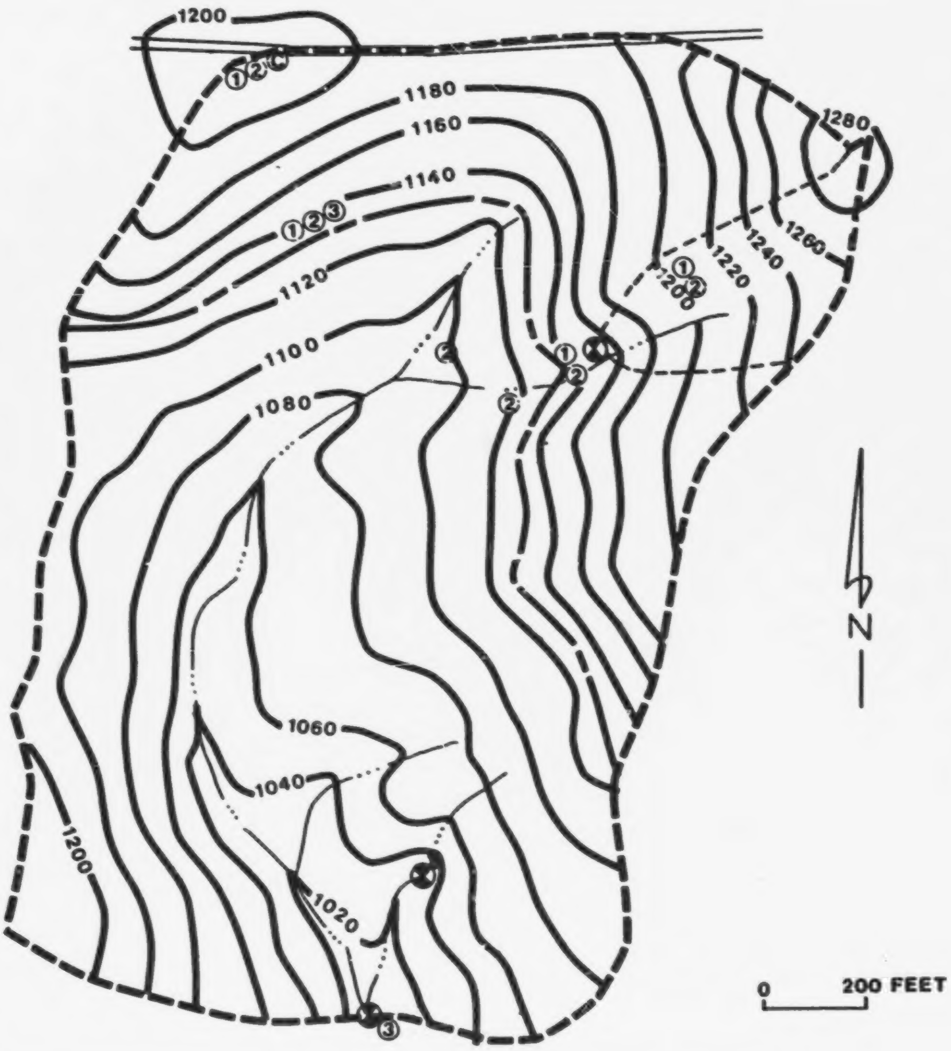
Figure 5. Premining Topographic Map of Watershed J08 Showing Proposed and Existing Instrumentation Sites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1160
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1120
1100
1080
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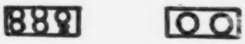
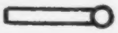
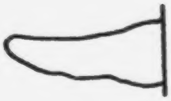
1020
1200
1280
1260
1240
1220
1200
①②
①②
②
②
③
N
0
200 FEET

Figure 6. Topographic Map of Control (Unmined) Watershed A06 Showing Instrumentation Sites

Table 2. Legend for Map Symbols

INSTRUMENT PLOT	
STANDARD PLOT WITH GAGE	
SPRING DEVELOPMENT	▭
CORE SITE	©
WELL MONITORING - 2ND AQUIFER	②
SEDIMENT POND	
GAGING STATION	⊗
WATERSHED BOUNDARY	– – – – – – – –
INTERMITTENT STREAMS	
CONTOUR LINE	——— 200 ———
COAL OUTCROP	
SOIL MOISTURE ACCESS TUBE	+
INFILTROMETER SITE	1B

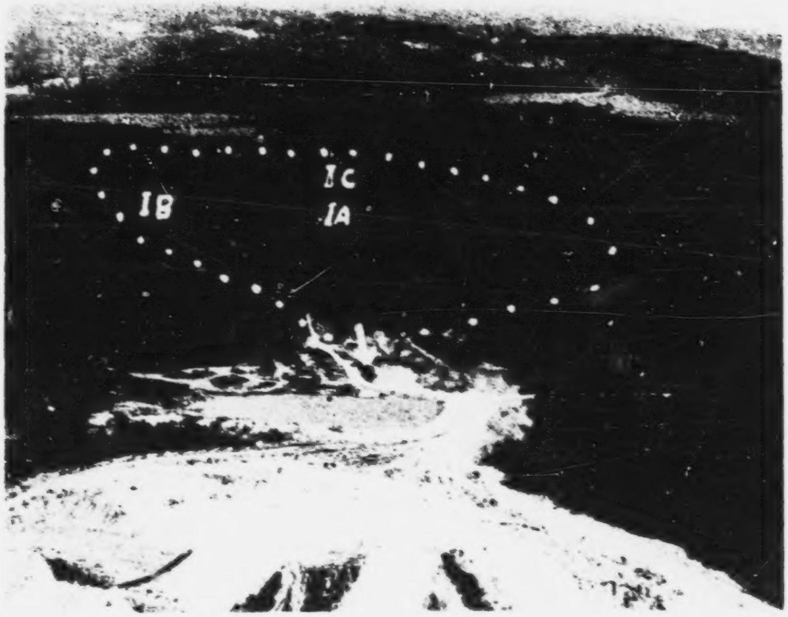


Figure 7. Oblique Aerial Photograph of Control Watershed (Watershed C06)

Figure 8. Premining Oblique Aerial Photograph of Watershed M09

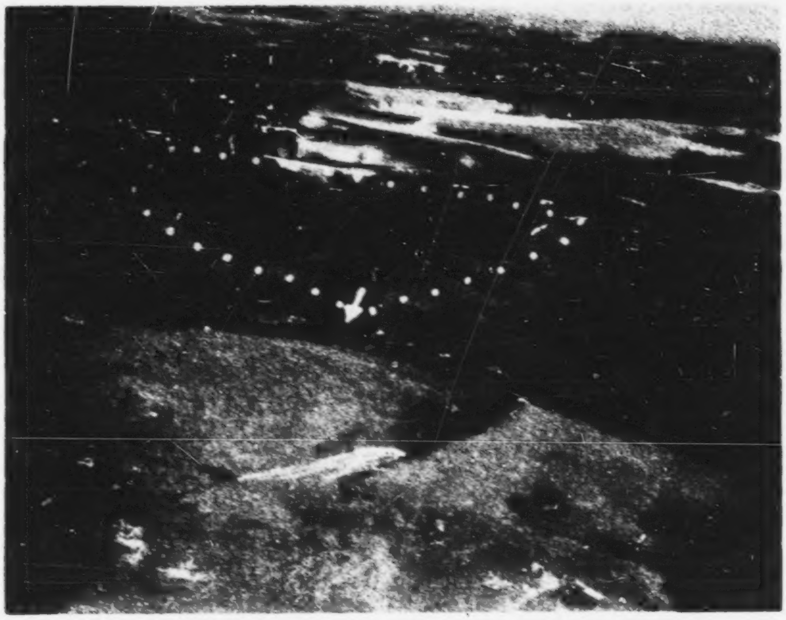


Figure 9. Premining Oblique Aerial Photograph of Watershed J11

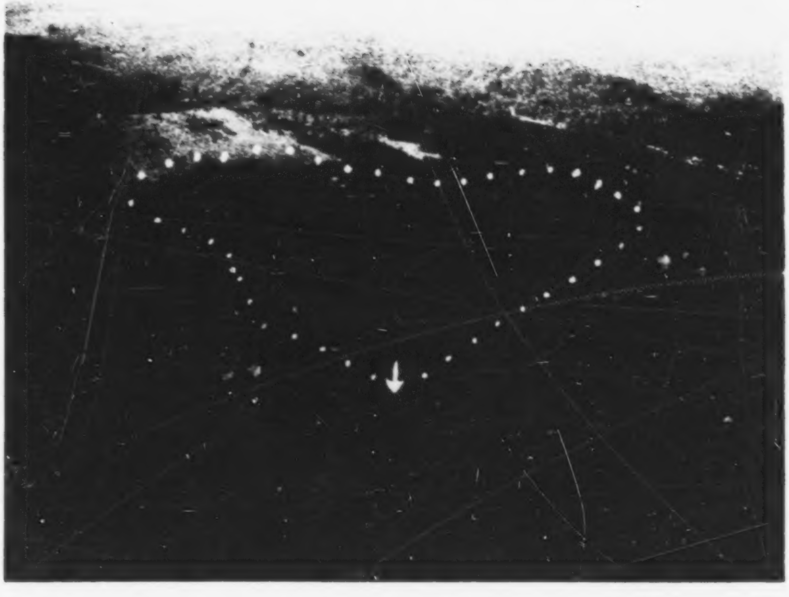


Figure 10. Premining Oblique Aerial Photograph of Watershed J08

Table 3. Physical Characteristics of the Study Watersheds.

Item	Watershed				
	C06	M09	J11	J08	A06
Area (Ac.)	49.0	43.5	29.1	44.8	43.6
Aspect	SE	SSE	W	S	S
Maximum Elevation (ft., sld)	1075	1165	1280	1200	1290
Minimum Elevation (ft., sld)	810	933	1135	880	1008
Relief (ft.)	265	232	145	320	282
Approx. Elevation of Coal (ft.,sld)	928	1000	1190	1025	1130
Length of Main Watercourse (ft.)	2000	1800	1400	1200	1750
Expected Disturbance (%)	91	80	77	15[1]	0.0[2]

[1] Limited outcrop haul-back mining of watershed previously deep mined.

[2] Control watershed; not to be mined.

C. Soils

1. Introduction

The soils in the watersheds scheduled for mining (Watersheds C06, M09, J08, and J11) were mapped by USDA - Soil Conservation Service personnel working in the area and using county and state soil legends. Mapping information for watershed A06 has already been published (Kelley et al, 1975), and only limited information will be presented.

Mapping units are distinguished from each other according to soil series, percent slope, and degree of erosion. A given mapping unit is identified by a pair of letters, the first capital and the second small case representing soil type; a second capital letter B, C, D, E, F, or G representing slope (symbols without a slope letter are those of nearly level soils); and a final number representing the degree of erosion. The soil mapping units and their identification, along with slope and erosion classes that were mapped, are given in Table 4 for the study watersheds. (Slope and erosion codes are given in Table 5). Capital letters A, B, C, or D, shown in Table 4, are used to indicate soil hydrologic classification, but are not included in a mapping unit symbol.

In the following sections the soil mapping units delineated for each watershed are listed and mapped. In Appendix A, complete soil descriptions and characterization data are given for the most extensive and representative soils that were sampled in the study watersheds. Typical or modal descriptions and ranges in characteristics for the remaining soil mapping units will be included in a future supplement to this report.

Table 4. Soils Mapped on the Premined Study Watershed Sites.

Soil Ident.	Soil Type	Hydrologic Soil Class.	Study Watersheds (Slope - Erosion Classes)				
			A06	C06	M09	J11**	J08**
Ah	Allegheny Silt Loam	B		D1, E1			
Be	Berks Silt Loam	C				G	
Br	Berks Shaly Silt Loam	C	C2,E2,F2				
Bs	Berks Channery Silt Loam	C			G2		
Bt	Brookside Silt Loam	C			C2,D2		
Cl	Clarksburg Silt Loam	C		E1			
Co	Coshocton Silt Loam	C		C1,E1,F1	D2	C2,D2	
Cr	Coshocton-Rayne Complex	C	D2,F2				
Cu	Culleoka Silt Loam	C				F2	
Dk	Dekalb Channery Sandy Loam	B	C2,D2,E2,F2				
Dl	Dekalb Loam and Sandy Loam	B		F1,G1			
El	Elba Silty Clay Loam	C			C2,D2,F6		
Em	Elba Silt Loam	C					F1
Gi	Gilpin Silt Loam	C				C2,D2	B2,C2,D2,F1
Gr	Guernsey Silt Loam	C					E1

Table 4. (Cont'd) Soils Mapped on the Premined Study Watershed Sites.

Soil Ident.	Soil Type	Hydrologic Soil Class.	Study Watersheds (Slope - Erosion Classes)				
			A06	C06	M09	J11**	J08**
Kp	Strip Mine Spoil, Acid Fine Loam Skeletal	None					C2,E2,G
Li	Licking Silt Loam	C			C2		
Lo	Lowell Silt Loam	C			E6		
Ms	Muskingum Silt Loam	C		D1,G1			
Or	Orville Silt Loam	C			*		
Ot	Otwell Silt Loam	C		D1,E1			
Ra	Ramsey Sandy Loam	B			E2		
Re	Rayne Silt Loam	C	C2				
Up	Upshur Silt Loam	C			F2		
Ur	Upshur Clay	D			D2,E2,E2		
Wd	Wayland Silt Loam	C/D		*			
We	Westmore Silt Loam	C			C2,D2		
Wf	Westmoreland Silt Loam	C		C1,D1,E1,F1	C1,C2,E2		G1
Wt	Woodsfield Silt Loam	C			E2		

*Indicates the soil is present, but no slope or erosion codes given in soil survey.
**Subject to change following laboratory analyses of selected pedons.

Table 5. Slope and Erosion Codes

Slope Legend

On Soils		On Spoils	
Code	Slope %	Code	Slope %
A	0-2		
B	2-6	B	0-6
C	6-12	C	6-12
D	12-18		
E	18-25	E	12-25
F	25-35		
G	>35	G	>25

Erosion Legend

Code	Erosion
1	Mostly Top Soil
2	Mixture of Topsoil and Subsoil
3	Mostly Subsoil
6	Slips are Common

2. Watershed C06

A total of 26 soil delineations were made in the watershed, and the soil mapping units and their areas are listed in Table 6. The soil map for Watershed C06 is presented in Figure 11.

Table 6. Names and Areas of Soil Mapping Units Delineated for Watershed C06.

Soil Mapping Unit	Area (Ac.)
Allegheny D1 and E2	3.3
Clarksburg E1	2.4
Coshocton C1, E1, and F1	5.8
Dekalb F1 and G1	15.7
Muskingum D1 and G1	2.9
Otwell D1 and E1	4.6
Wayland[1]	1.2
Westmoreland C1, D1, E1, and F1	13.1
Total (Ac.)	49.0

[1] No slope or erosion codes given in soil survey.

a. Soil Sampling

Five sites including four of the most extensive and representative soils, Otwell, Dekalb, Coshocton, and Westmoreland, were selected to be sampled for complete characterization. Soil pits were dug using a backhoe or where inaccessible, by hand, and the soils were described and sampled in August, 1976. Description and characterization data for the soils are included in Appendix A. Brief descriptions are as follows:

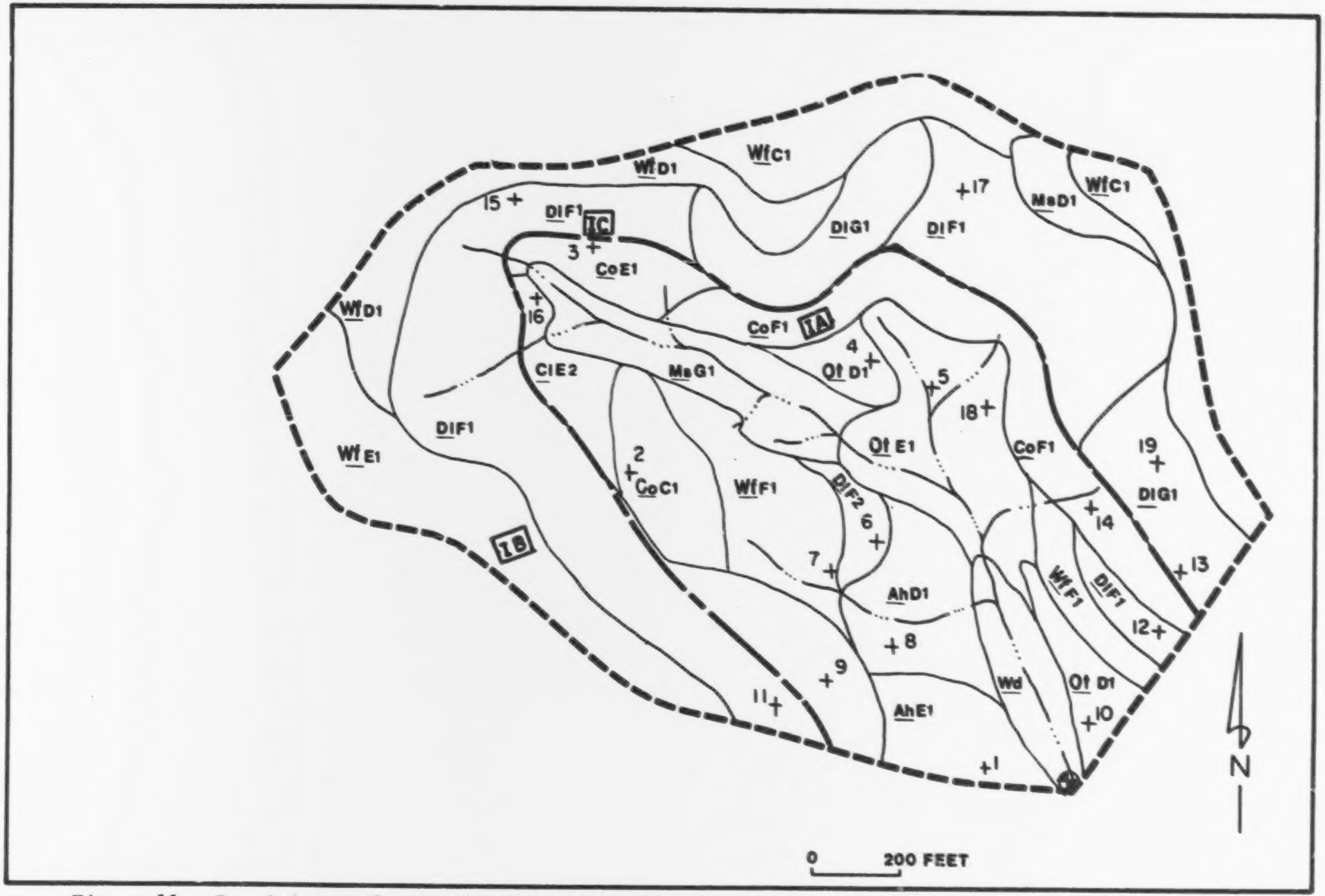

WfC1
WfD1
DIF1
IC
15
3
CoE1
DIG1
17
DIF1
MaD1
WfC1
WfD1
16
CoF1
IA
4
OfD1
MaG1
CIE2
5
18
DIF1
WfE1
OfE1
CoF1
19
2
CoC1
WfF1
DIF2
6
DIG1
14
IB
7
13
AhD1
WfF1
DIF1
12
8
9
Wd
OfD1
11
AhE1
10
1
N
0
200 FEET

Figure 11. Premining Soils Map for Watershed C06

Dekalb - The soil described and sampled is within the range of the concept of the Dekalb series. This soil is a deep fragmental acid soil with large pieces of sandstone in much of the solum. The sandstone pieces are tipped at various angles indicating that they have moved downslope. Clay films are described deep in the solum indicating either deep percolation through these relatively coarse textured soils or an earlier period of pedogenesis prior to colluviation of the coarser surficial material.

Westmoreland - These soils formed in a shallow loess mantle and the underlying siltstone bedrock. The bedrock occurred at a depth of 33 inches in the pedon sampled. The soils are very strongly acid and have base saturations of less than 40 percent except in the surface horizon and just above the bedrock where base saturations are significantly higher. The base saturation increase just above the bedrock is important in the classification of these soils as alfisols rather than ultisols. The soils in the watershed are somewhat finer textured than most Westmoreland soils. Plant growth in these soils is somewhat limited by acidity, low base status, and relatively shallow rooting depth.

Coshocton - These are loamy colluvial soils which overly shale or siltstone bedrock. The pH and base saturation values of the two pedons sampled in this watershed exhibit opposite extremes. The base saturations in both pedons are outside the range for Coshocton series with base saturation of pedon CS-30 being too low and CS-32 too high as carbonates occur in the latter. However, this represents the range in properties of Coshocton soils as they occur in this watershed.

Otwell - These soils are typically found on high terraces or benches in eastern and southeastern Ohio. The Otwell soils in this watershed formed in a thin mantle of colluvial material and the underlying lacustrine deposit. The soils are silty throughout the solum and have a fragipan starting at about 2 feet below the surface. Base saturation is relatively low from the surface to the base of the fragipan; base saturation then increases with depth. The low coarse fragment content and silty texture of this soil makes it an excellent source of material for topsoiling.

The Dekalb and Westmoreland soils pose the most serious problems for plant growth. Both soils have a relatively low cation exchange capacity and are quite acid. Dekalb also has a high content of coarse fragments whereas the rooting depth in Westmoreland is somewhat restricted by bedrock. Both Coshocton and Otwell pose few problems limiting vegetative growth; however, the rooting depth in Otwell is somewhat restricted by a fragipan. Both Coshocton and Otwell soils can provide suitable topsoil material with Otwell being an excellent source.

3. Watershed M09

A total of 33 soil delineations were made in the watershed, and the soil mapping units and their areas are listed in Table 7.

The soil map for Watershed M09 is presented in Figure 12.

Table 7. Names and Areas of Soil Mapping Units Delineated for Watershed M09.

Soil Mapping Unit	Area (Ac.)
Berks G2	0.9
Brookside C2 and D2	3.7
Coshocton D2	0.6
Elba C2, D2, and F6	5.3
Licking C2	3.0
Lowell E6	2.6
Orville E6	0.6
Upshur D2, E2, E3, and F2	8.9
Westmore C2	12.7
Westmoreland C1, C2, and E2	2.8
Woodsfield E2	2.4
Total (Ac.)	43.5

a. Soil Sampling

Five of the most extensive and representative soils, Lowell, Upshur, Westmore, Licking, and Brookside, were selected to be sampled for complete characterization. Soil pits were dug using a crawler tractor and blade. The soils were described and sampled in February, 1977. Descriptions and characterization data for the soils are included in Appendix A. Brief descriptions are as follows:

Lowell - This soil developed in loess-colluvium overlying shale bedrock. The Lowell soils of the watershed are typical of the Lowell series with a silty upper solum overlying a heavy-textured lower solum. Base saturation increases with depth.

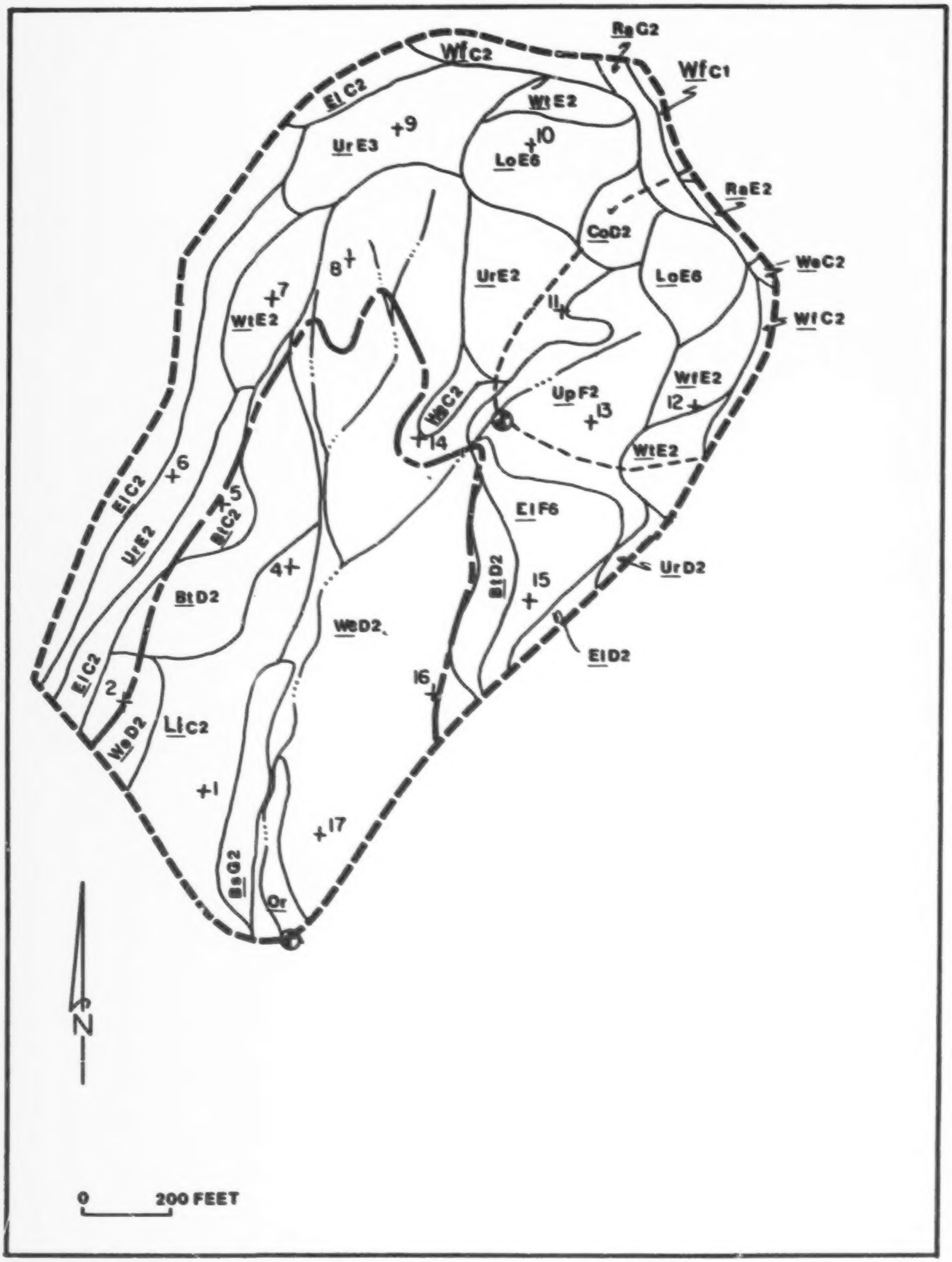

RaG2
WfC2
WfC1
ElC2
UrE3
+9
WtE2
+10
LoE6
RaE2
CoD2
WaC2
8+
+7
UrE2
LoE6
WtE2
11
WfC2
WaC2
UpF2
WtE2
12
14
13
WtE2
ElC2
6
UrE2
5
BtC2
ElF6
4
BtD2
WaD2
BtD2
15
UrD2
ElD2
ElC2
2
16
WaD2
LiC2
1
17
BaG2
Or
N
0
200 FEET

Figure 12. Premining Soils Map for Watershed M09

Upshur - This is a very heavy-textured soil with carbonates in the shale at a depth of 48 inches. The Upshur in the watershed is within the range of the series as described on the state legend.

Westmore - These soils formed in a thin loess mantle and the underlying silty colluvium. The soils in this watershed are more acid than typical for Westmore but still have base saturations which are high enough for classification as alfisols. The soils are also lighter textured and contain less coarse fragments in the lower part of the sola than is typical for Westmore soils.

Licking - These soils formed in a thin loess mantle and the underlying clayey lacustrine deposit. Even though these soils are strongly to medium acid, base saturation is relatively high throughout the profile with carbonates occurring at 57 inches. In fact, the base saturation in the upper part of the solum is higher than typical for Licking soils. As a result of the high base status and high cation exchange capacity, these soils are relatively productive. Permeability is somewhat restricted due to the high clay content.

Brookside - Brookside soils typically developed in colluvium at the base of long slopes. The soil as delineated in the M09 watershed fits this concept, and the profile sampled fits the series concept. At the sample site, two buried surfaces were identified. This observation is supported by laboratory data. Several of the horizons have high carbonate contents, probably derived from seepage.

In general the soils of the M09 watershed were finer textured and had a higher base saturation than the C06 watershed. Available moisture holding capacity was high in most of the soils. Texture, CEC, and base status made these soils well suited for plant growth except where there was a high clay content near the surface. With the exception of the Upshur mapping unit and other areas where high clay contents were found near the surface, the soils of the watershed were very good for topsoiling. The most serious problem with these soils is their relatively low permeability as a result of high clay contents.

4. Watershed J11

A total of 10 soil delineations were made in the watershed and the soil mapping units and their areas are listed in Table 8.

The soils map for Watershed J11 is presented in Figure 13.

Soil sampling for J11 has not been completed and information, when available, will be submitted in subsequent phase reports. Some soil mapping unit names may be changed following receipt of laboratory analyses.

Table 8. Names and Areas of Soil Mapping Units Delineated for Watershed J11

Soil Mapping Unit	Area (Ac.)
Berks G	1.1
Coshocton C2 and D2	3.8
Culleoka F2	0.9
Gilpin C2 and D2	23.3
Total (Ac.)	29.1

5. Watershed J08

A total of 13 soil delineations were made in the watershed and the soil mapping units and their areas are listed in Table 9.

Table 9. Names and Areas of Soil Mapping Units Delineated for Watershed J08.

Soil Mapping Unit	Area (Ac.)
Elba F1	8.1
Gilpin B2, C2, D2, and E1	17.5
Guernsey E1	8.0
Strip Mine Spoil C2, E2, and G	4.2
Westmoreland G1	7.0
Total (Ac.)	44.8

The soils map for Watershed J08 is presented in Figure 14.

Soil sampling has not been completed on Watershed J08 and such information, when available, will be submitted in a supplement to the Phase 1 Report. Some soil mapping unit names may be changed following receipt of laboratory analyses.

6. Watershed A06

Soils information for Watershed A06 has been published (Kelly et al, 1975). This watershed, located at the USDA - North Appalachian Experimental Watershed, is referred to as Watershed 172 in previous publications, (Langford and McGuinness, 1976).

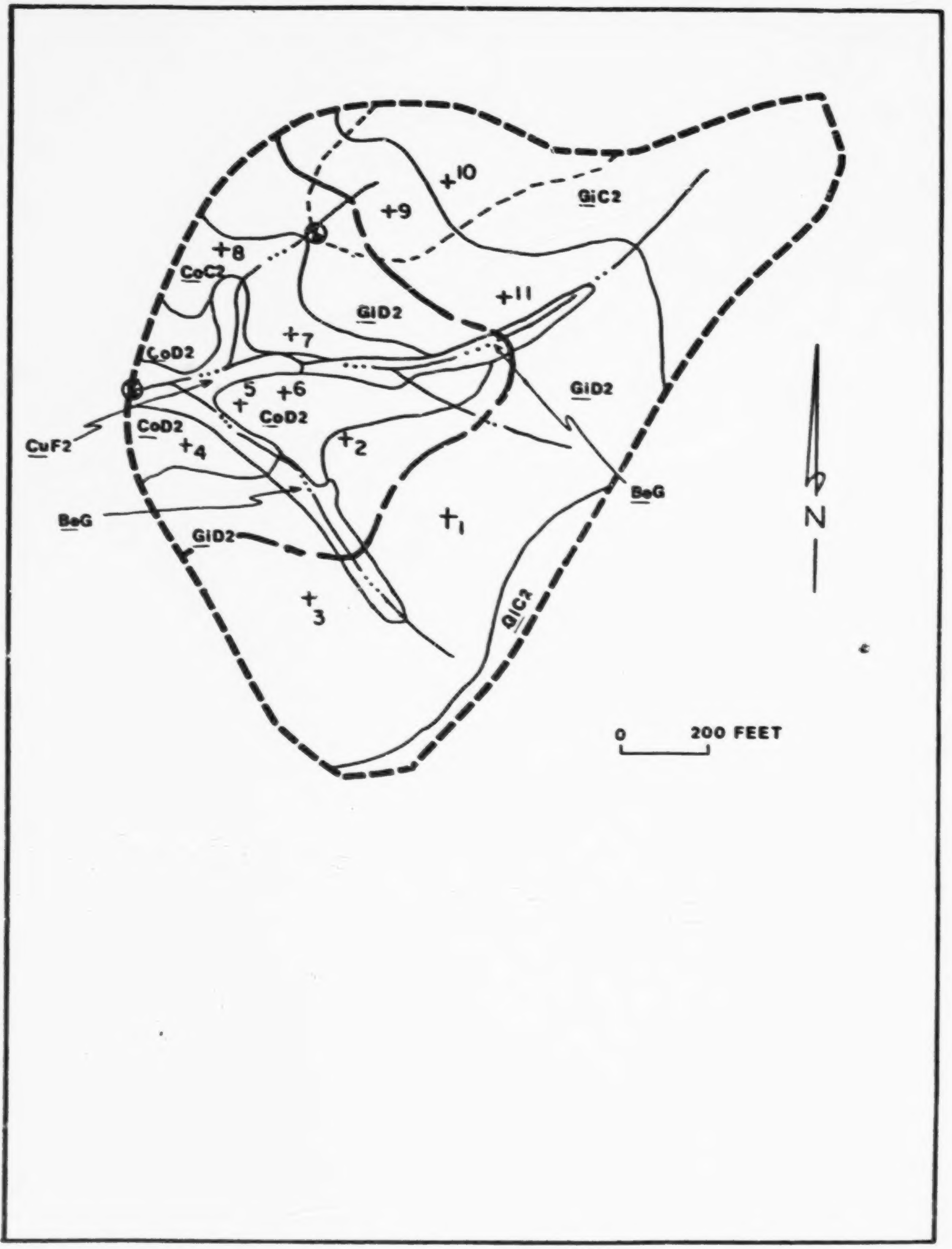

+10
GiC2
+9
+8
CoC2
+11
GlD2
+7
CoD2
5
+
+6
CoD2
GlD2
CuF2
CoD2
+4
+2
BeG
BeG
+1
GlD2
+3
GiC2
N
0
200 FEET

Figure 13. Premining Soils Map for Watershed J11

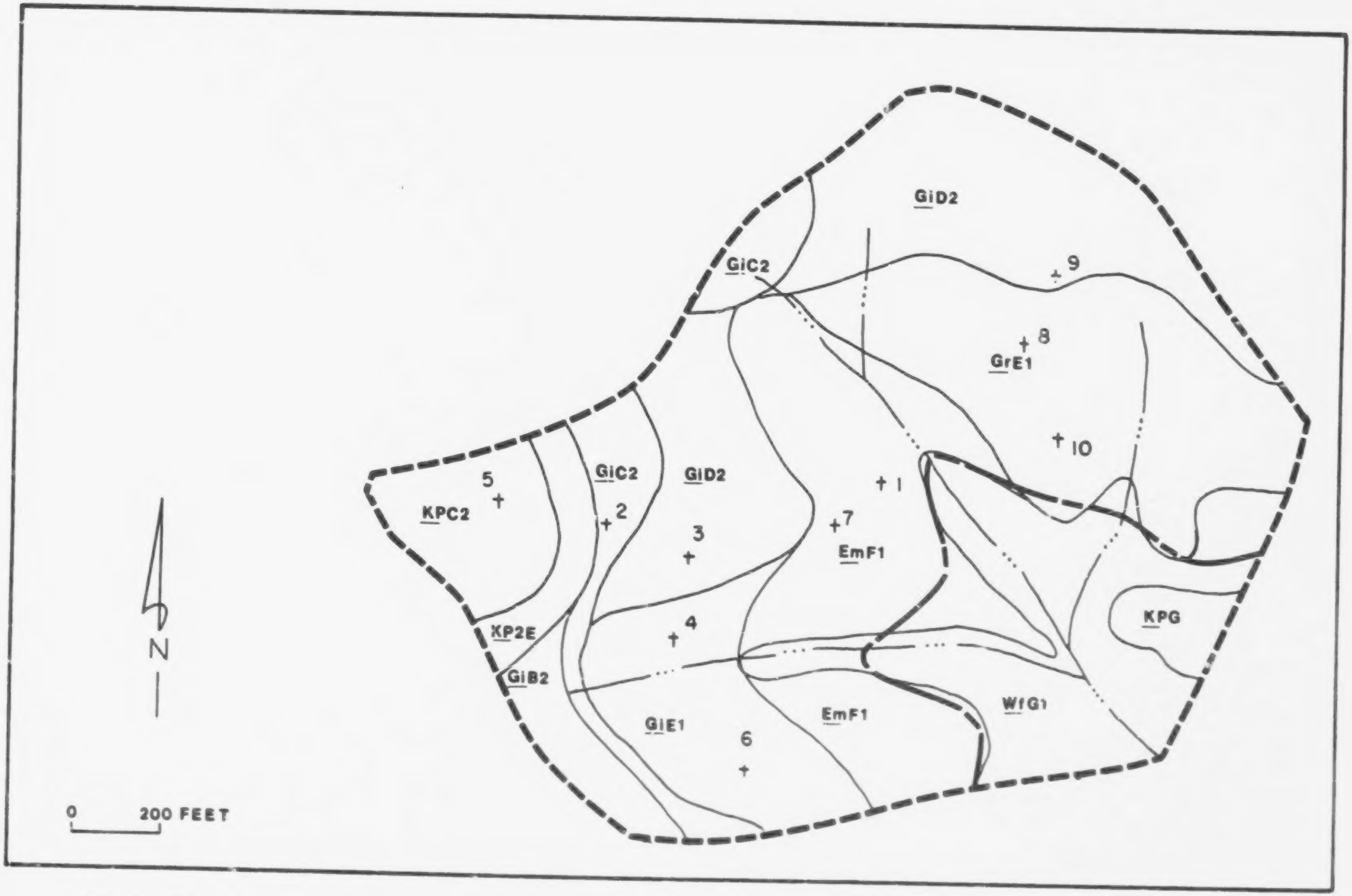

GiD2
GiC2
9
8
GrE1
10
5
KPC2
GiC2
GiD2
1
2
3
7
EmF1
KPG
4
KP2E
GiB2
GiE1
6
EmF1
WfG1
N
0
200 FEET

Figure 14. Premining Soils Map for Watershed J08

Soil mapping units and their areas are listed in Table 10.

Table 10. Names and Areas of Soil Mapping Units Delineated for Watershed A06.

Soil Mapping Unit	Area (Ac.)
Berks C2, E, and F2	24.9
Coshocton-Rayne Complex D2, F2	13.3
Dekalb C2, D2, E2, and F2	4.6
Rayne C2	0.8
Total (Ac.)	43.6

The soils map for Watershed A06 is presented in Figure 15.

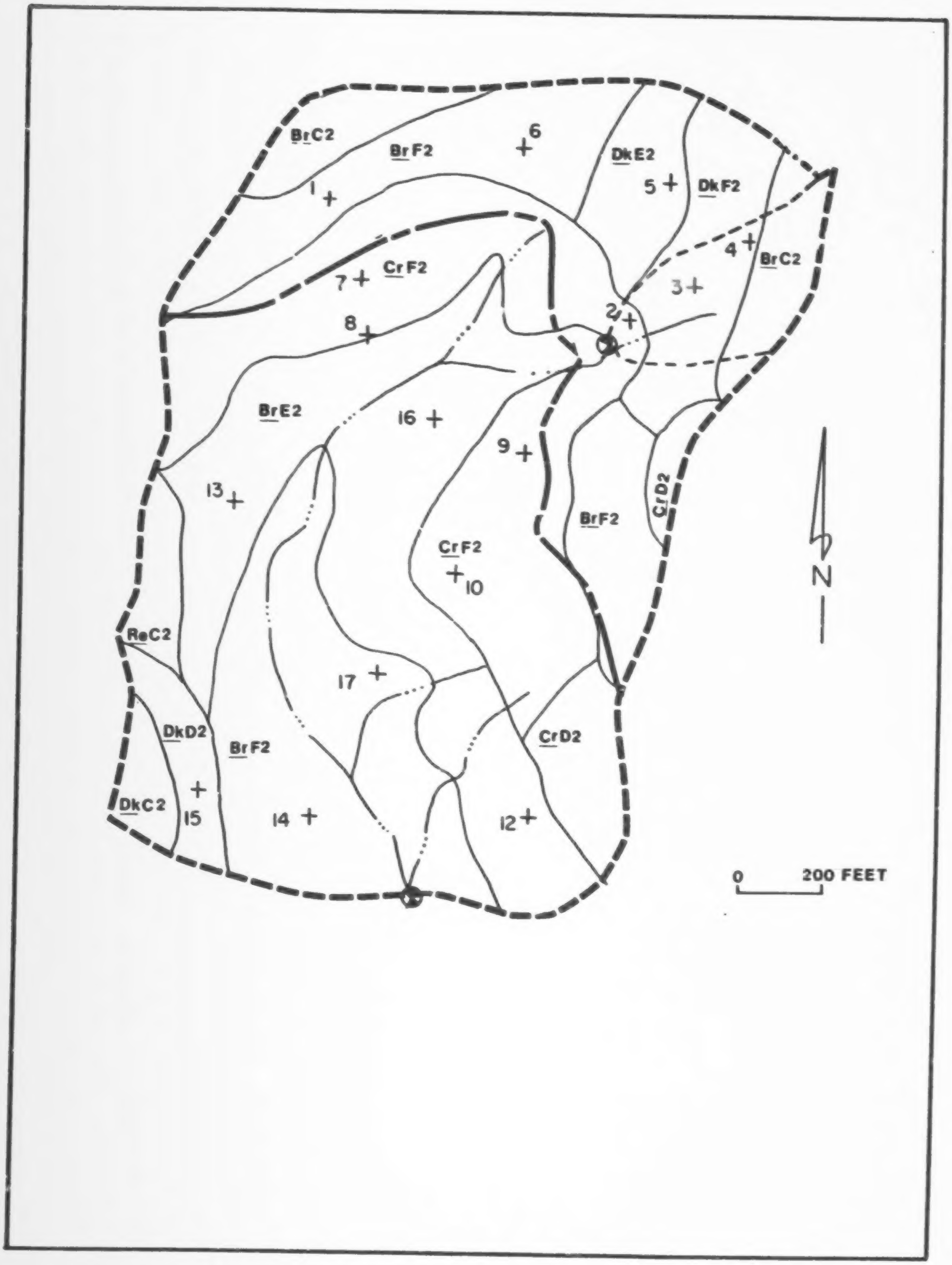

BrC2
BrF2
6
DkE2
5
DkF2
1
7
CrF2
4
BrC2
3
2
8
BrE2
16
9
13
CrD2
BrF2
CrF2
10
N
ReC2
17
DkD2
BrF2
CrD2
DkC2
15
14
12
0
200 FEET

Figure 15. Soils Map for Unmined Watershed A06

D. Geology

1. Introduction

The study watersheds are in the unglaciated plateau region. Each study watershed is underlain by stratified sedimentary rocks of the Pennsylvania System. The rocks consist of shale, siltstone, sandstone, limestone, coal, and clay. They were deposited in shallow-marine or shoreline environments, then subjected to crustal uplift resulting in fracturing and a slight regional southeasterly dip. Now partly eroded, the rocks present a hilly topography characteristic of the region. Several feet of weathered rock and soil overlie the bedrock in most places.

Lithology and approximate maximum thickness of overburden above coals in each watershed are shown by stratigraphic columns (Figures 16-20). Ohio coals are of high-volatile, bituminous rank, and analyses generally show ash content of 5-20 percent, sulfur 1-6 percent, and heating value from slightly below 10,000 to over 13,000 Btu/lb. (Collins, 1978, p. 532-534).

Locations at which geologic cores were obtained are shown in Figures 2-6 (three different locations were used at C06). Physical and chemical data for the C06, M09, J11, and J08 cores are presented in Appendix B.

2. Watershed C06

The geology of Coshocton County, within which both watersheds C06 and A06 are located, was described by Lamborn (1954). Sandstone and shale were the prevalent rock types at C06 (see stratigraphic column, Figure 16). The No. 6 coal was the only coal that occurred above the mouth of the watershed.

3. Watershed M09

The geology of Muskingum County was described by Stout (1918). The stratigraphy of the M09 watershed (Figure 17) was characterized by limestone, shale, and several coal seams. The mouth of the watershed was at the level of the No. 8 coal.

4. Watershed J11

Details of the geology of Jefferson County, within which J11 and J08 are located, were given by Lamborn (1930). The highest part of the stratigraphy at J11 consisted of rocks of the Permian System, (Figure 18). Limestone, sandstone, and shale, comprised significant parts of the rock section. The mouth of the watershed was at a level between the No. 9 and No. 10 coals.

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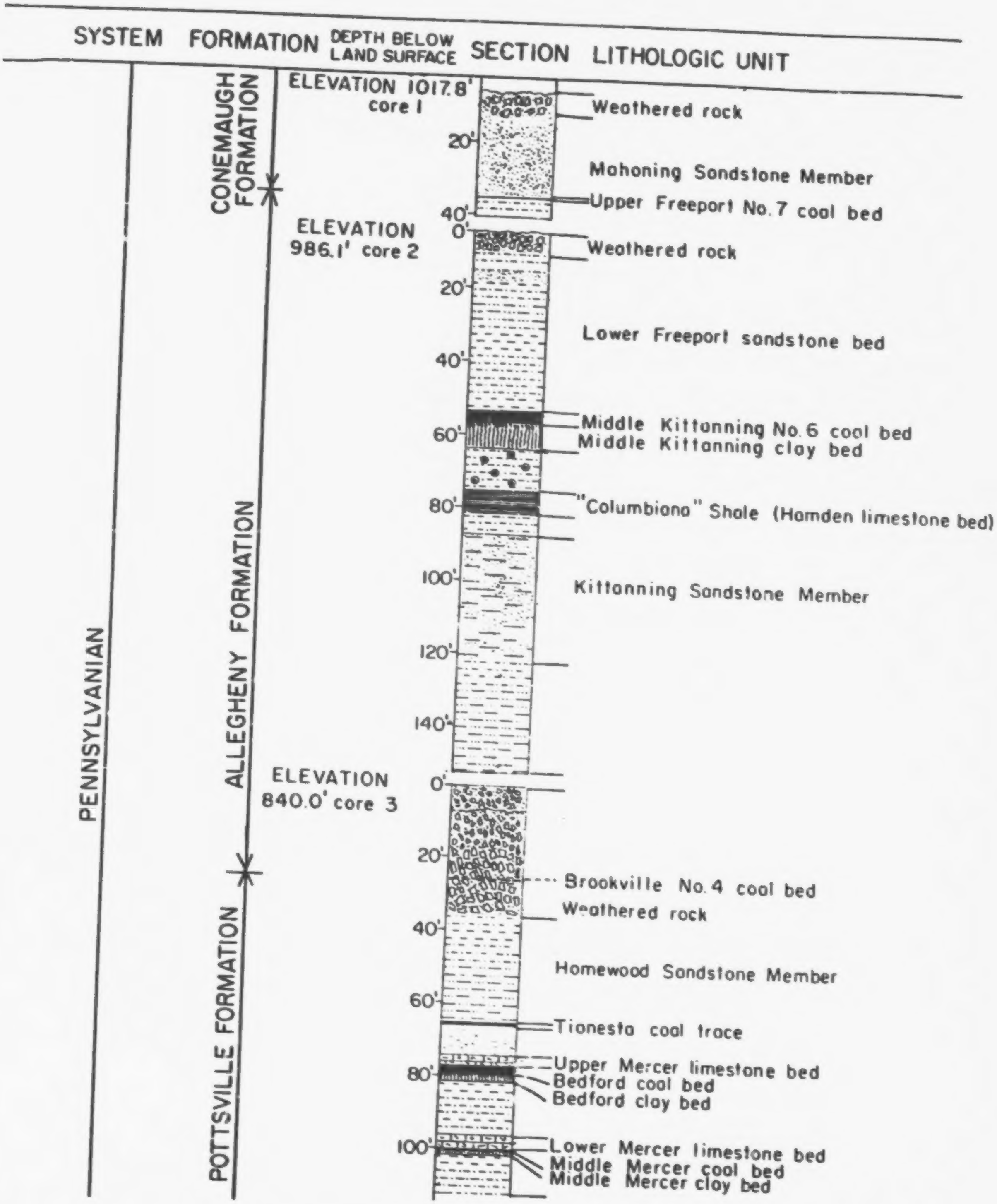
SYSTEM
FORMATION
DEPTH BELOW LAND SURFACE
SECTION
LITHOLOGIC UNIT
PENNSYLVANIAN
CONEMAUGH FORMATION
ALLEGHENY FORMATION
POTTSVILLE FORMATION
ELEVATION 1017.8' core 1
ELEVATION 986.1' core 2
ELEVATION 840.0' core 3
20'
40'
0'
20'
40'
60'
80'
100'
120'
140'
0'
20'
40'
60'
80'
100'
Weathered rock
Mahoning Sandstone Member
Upper Freeport No. 7 coal bed
Weathered rock
Lower Freeport sandstone bed
Middle Kittanning No. 6 coal bed
Middle Kittanning clay bed
"Columbiana" Shale (Hamden limestone bed)
Kittanning Sandstone Member
Brookville No. 4 coal bed
Weathered rock
Homewood Sandstone Member
Tionesta coal trace
Upper Mercer limestone bed
Bedford coal bed
Bedford clay bed
Lower Mercer limestone bed
Middle Mercer coal bed
Middle Mercer clay bed

Figure 16. Stratigraphic Column for C06

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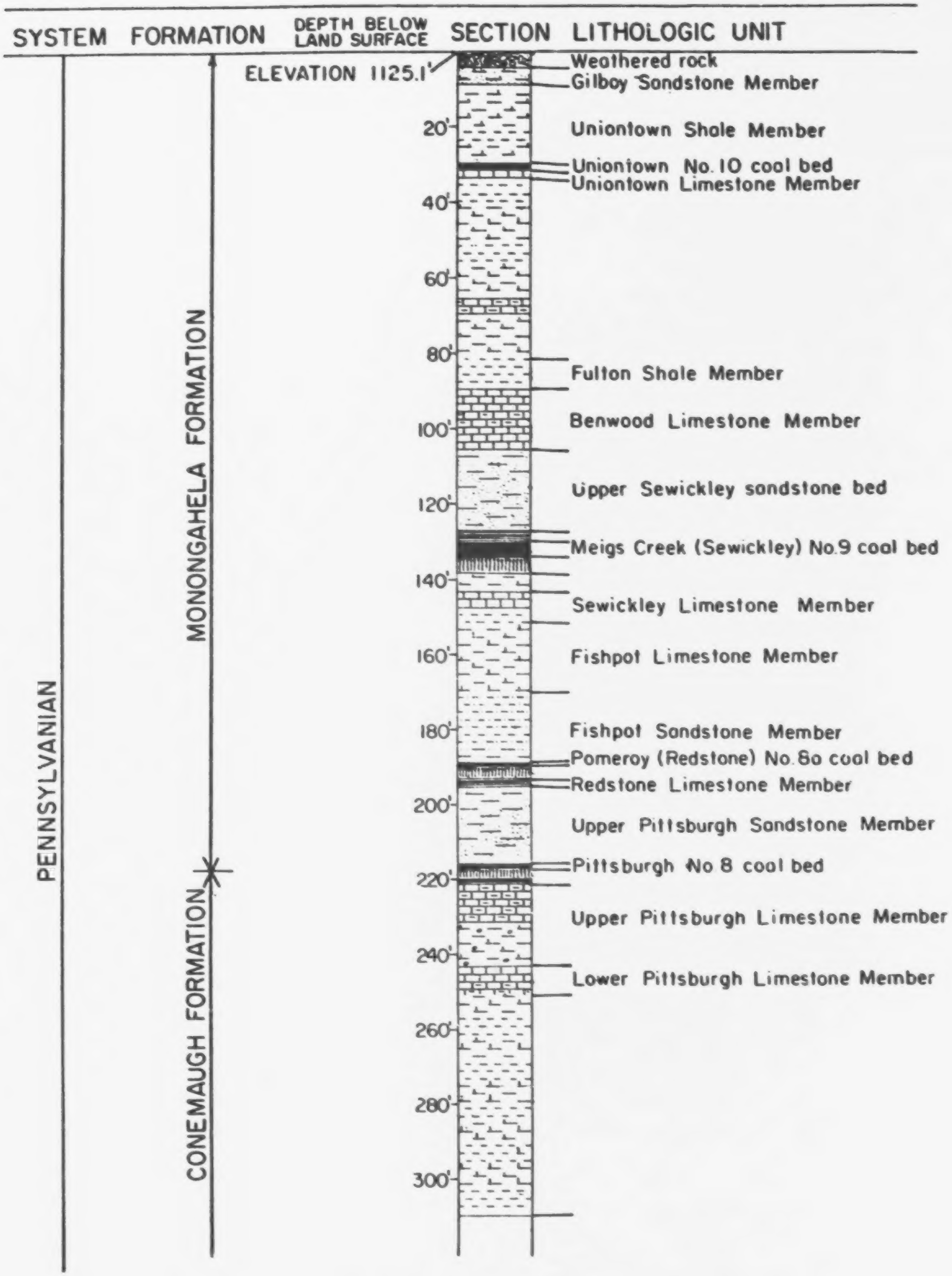
SYSTEM
FORMATION
DEPTH BELOW LAND SURFACE
SECTION
LITHOLOGIC UNIT
ELEVATION 1125.1'
PENNSYLVANIAN
MONONGAHELA FORMATION
CONEMAUGH FORMATION
20'
40'
60'
80'
100'
120'
140'
160'
180'
200'
220'
240'
260'
280'
300'
Weathered rock
Gilboy Sandstone Member
Uniontown Shale Member
Uniontown No. 10 coal bed
Uniontown Limestone Member
Fulton Shale Member
Benwood Limestone Member
Upper Sewickley sandstone bed
Meigs Creek (Sewickley) No. 9 coal bed
Sewickley Limestone Member
Fishpot Limestone Member
Fishpot Sandstone Member
Pomeroy (Redstone) No. 8a coal bed
Redstone Limestone Member
Upper Pittsburgh Sandstone Member
Pittsburgh No 8 coal bed
Upper Pittsburgh Limestone Member
Lower Pittsburgh Limestone Member

Figure 17. Stratigraphic Column for MO9

Microfilmed From
Best Available Copy

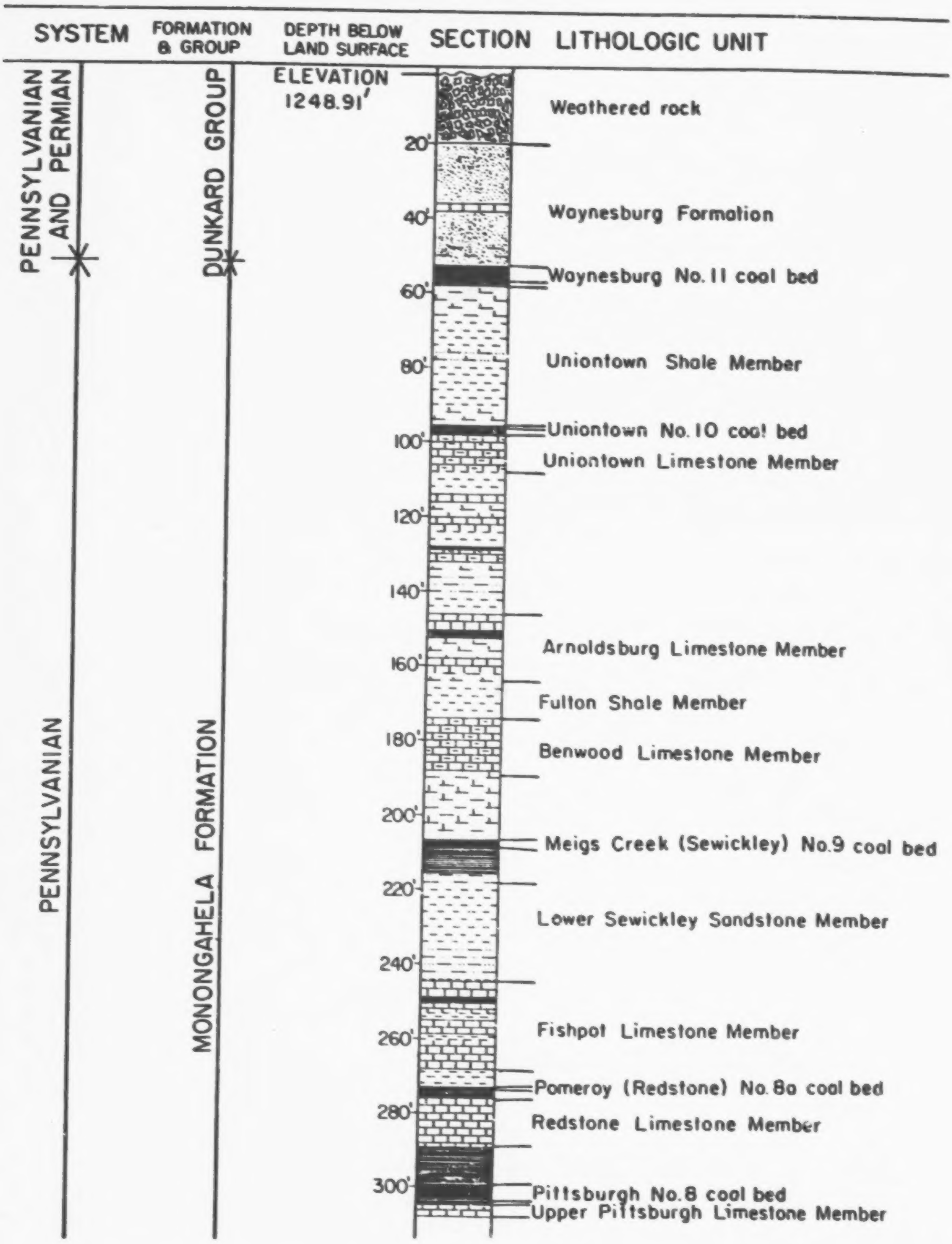
SYSTEM
FORMATION & GROUP
DEPTH BELOW LAND SURFACE
SECTION
LITHOLOGIC UNIT
PENNSYLVANIAN AND PERMIAN
PENNSYLVANIAN
DUNKARD GROUP
MONONGAHELA FORMATION
ELEVATION 1248.91'
20'
40'
60'
80'
100'
120'
140'
160'
180'
200'
220'
240'
260'
280'
300'
Weathered rock
Waynesburg Formation
Waynesburg No. 11 coal bed
Uniontown Shale Member
Uniontown No. 10 coal bed
Uniontown Limestone Member
Arnoldsburg Limestone Member
Fulton Shale Member
Benwood Limestone Member
Meigs Creek (Sewickley) No. 9 coal bed
Lower Sewickley Sandstone Member
Fishpot Limestone Member
Pomeroy (Redstone) No. 8a coal bed
Redstone Limestone Member
Pittsburgh No. 8 coal bed
Upper Pittsburgh Limestone Member

Figure 13. Stratigraphic Column for J11

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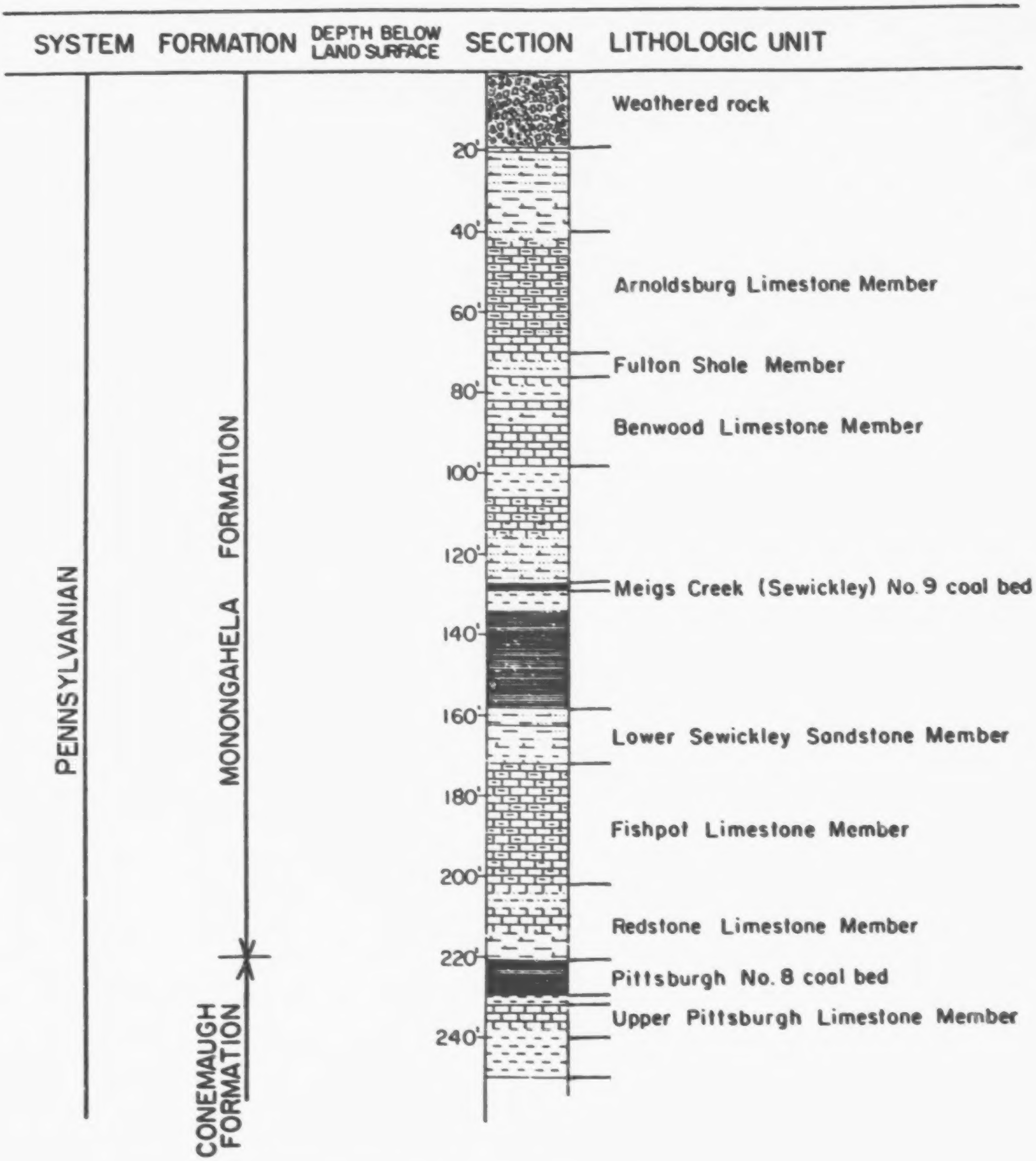
SYSTEM
FORMATION
DEPTH BELOW LAND SURFACE
SECTION
LITHOLOGIC UNIT
PENNSYLVANIAN
MONONGAHELA FORMATION
CONEMAUGH FORMATION
20'
40'
60'
80'
100'
120'
140'
160'
180'
200'
220'
240'
Weathered rock
Arnoldsburg Limestone Member
Fulton Shale Member
Benwood Limestone Member
Meigs Creek (Sewickley) No. 9 coal bed
Lower Sewickley Sandstone Member
Fishpot Limestone Member
Redstone Limestone Member
Pittsburgh No. 8 coal bed
Upper Pittsburgh Limestone Member

Figure 19. Stratigraphic Column for J08

Microfilmed From
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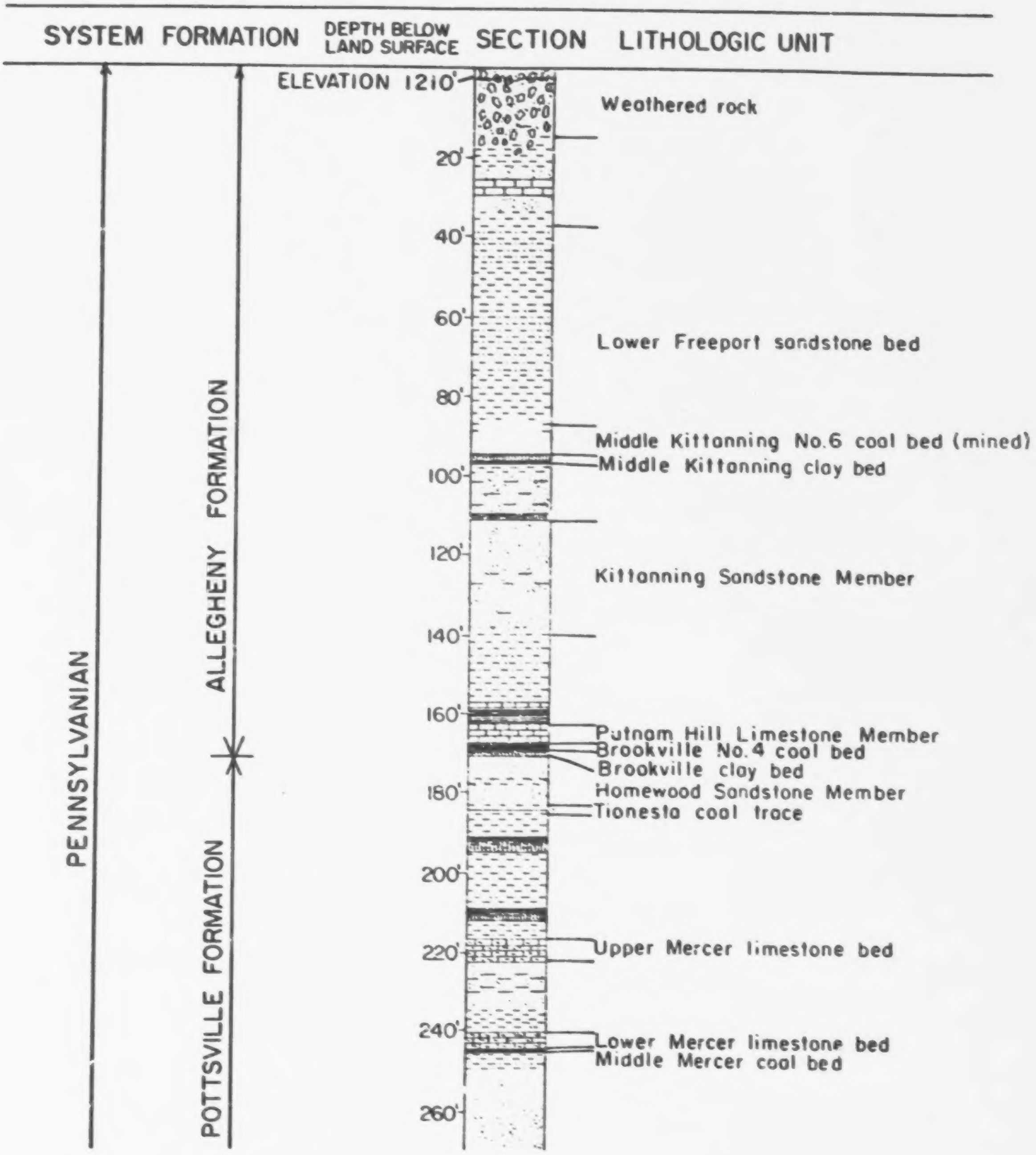
SYSTEM
FORMATION
DEPTH BELOW LAND SURFACE
SECTION
LITHOLOGIC UNIT
PENNSYLVANIAN
ALLEGHENY FORMATION
POTTSVILLE FORMATION
ELEVATION 1210'
20'
40'
60'
80'
100'
120'
140'
160'
180'
200'
220'
240'
260'
Weathered rock
Lower Freeport sandstone bed
Middle Kittanning No.6 coal bed (mined)
Middle Kittanning clay bed
Kittanning Sandstone Member
Putnam Hill Limestone Member
Brookville No.4 coal bed
Brookville clay bed
Homewood Sandstone Member
Tionesta coal trace
Upper Mercer limestone bed
Lower Mercer limestone bed
Middle Mercer coal bed

Figure 20. Stratigraphic Column for A06

5. Watershed J08

Limestone and shale were predominant rock types at J08 (Figure 19). The mouth of the watershed is below the No. 8 coal.

6. Watershed A06

The control watershed was underlain by the same part of the stratigraphic section as C06. Sandstone and shale were the main rock types (Figure 20).

E. Vegetation

1. Introduction

Vegetation surveys were made on each study watershed in its premined condition. The data obtained were generalized maps of the major overstory vegetation types, basal area of vegetation, and surveys of the vegetation surrounding soil moisture access tubes.

The vegetation cover maps were constructed by running transects at one-chain intervals across the watersheds and mapping changes in overstory cover type and density. Soil moisture access tubes on the watersheds provided centers of plots from which timber volume and ground cover measurements were made. Timber volumes were determined using a variable plot prism cruise. Distinctions were made between sawtimber size trees (12" and greater, dbh), pole-sized timber (5" to 11", dbh), and woody reproduction (1" to 5", dbh). Ground cover consisting of herbaceous vegetation, woody cover, duff cover, and bare soil and/or rock were the observed catagories for each access tube. The values for herbaceous vegetation were obtained by surveying a 1/100th acre plot around each tube (radius = 11.78 ft.). Other ground cover was established by averaging data from four 1/1000th acre plots (radius = 3.72) located in cardinal directions 10 feet from the soil moisture access tubes.

2. Watershed C06

The majority of the C06 site had a southerly aspect and species composition and growing conditions were generally poor. Total sawtimber volume was 542 board feet per acre. There was a high percentage of cull in nearly all trees, with a net volume of 354 board feet per acre. Major sawtimber species on the area were red elm, tulip-poplar, and red maple, with some hickory present. Gross volume of pole-sized timber was 41.2 cords per acre and net volume was 34.5 cords per acre. Major polesized species were tulip-poplar, red maple, red oak, and dogwood.

Distribution of woody reproduction was quite variable, ranging from 200 to 1400 stems per acre on various plots with an average of 544 stems per acre. Major species in this class were aspen, dogwood, black cherry, maple, red oak and musclewood. Ground cover was also quite variable. Herbaceous vegetation varied from 3 to 82 percent cover, woody vegetation from 3 to 30 percent, duff cover from 6 to 60 percent, and bare soil and/or rock from 0 to 36 percent. Average ground cover values for herbs, woody vegetation, duff cover and bare soil and/or rock were 32, 14, 38, and 16 percent, respectively.

Access tube number 9 was not surveyed because it was destroyed in the initial mining activity.

The vegetation map, its key, and the summary of cover surrounding the soil moisture access tubes are shown in Figure 21, and Tables 11 and 12, respectively.

3. Watershed M09

The site had a general southeasterly exposure and was mostly pasture land. Total sawtimber volume was approximately 554 board feet per acre and volume of pole-sized timber was 0.52 cords. Because of the uneven distribution of woody species, sampling error for saw and pole-sized timber was essentially 100 percent.

Woody species occurring on the site included sycamore, tulip-poplar, elm, red maple, red oak, white oak, and dogwood. Approximately 77 percent of the ground cover on the area was composed of a mixture of grasses and broadleaved herbs, 8 percent being woody vegetation (briars, etc.), and the remaining 15 percent was bare and/or covered with organic litter.

Soil moisture access tubes 9-16 were not surveyed because they had been destroyed by mining activities before the survey. The area involved is delineated in Figure 22.

The vegetation map, its key, and the summary of cover surrounding the soil moisture access tubes are shown in Figure 22 and Tables 13 and 14, respectively.

4. Watershed J11

The watershed had a westerly aspect, with northwest to southwest exposures predominating. In woodlands, overstory species included black locust, ash, red maple, black cherry, and a stand of ailanthus. Much of the area was in pasture, both open and wooded. One section was under cultivation. Nine vegetation cover types were classified.

Only 4 of 11 sample points were wooded, and average timber volumes were low. Gross sawtimber volume was 106 board feet per acre and net

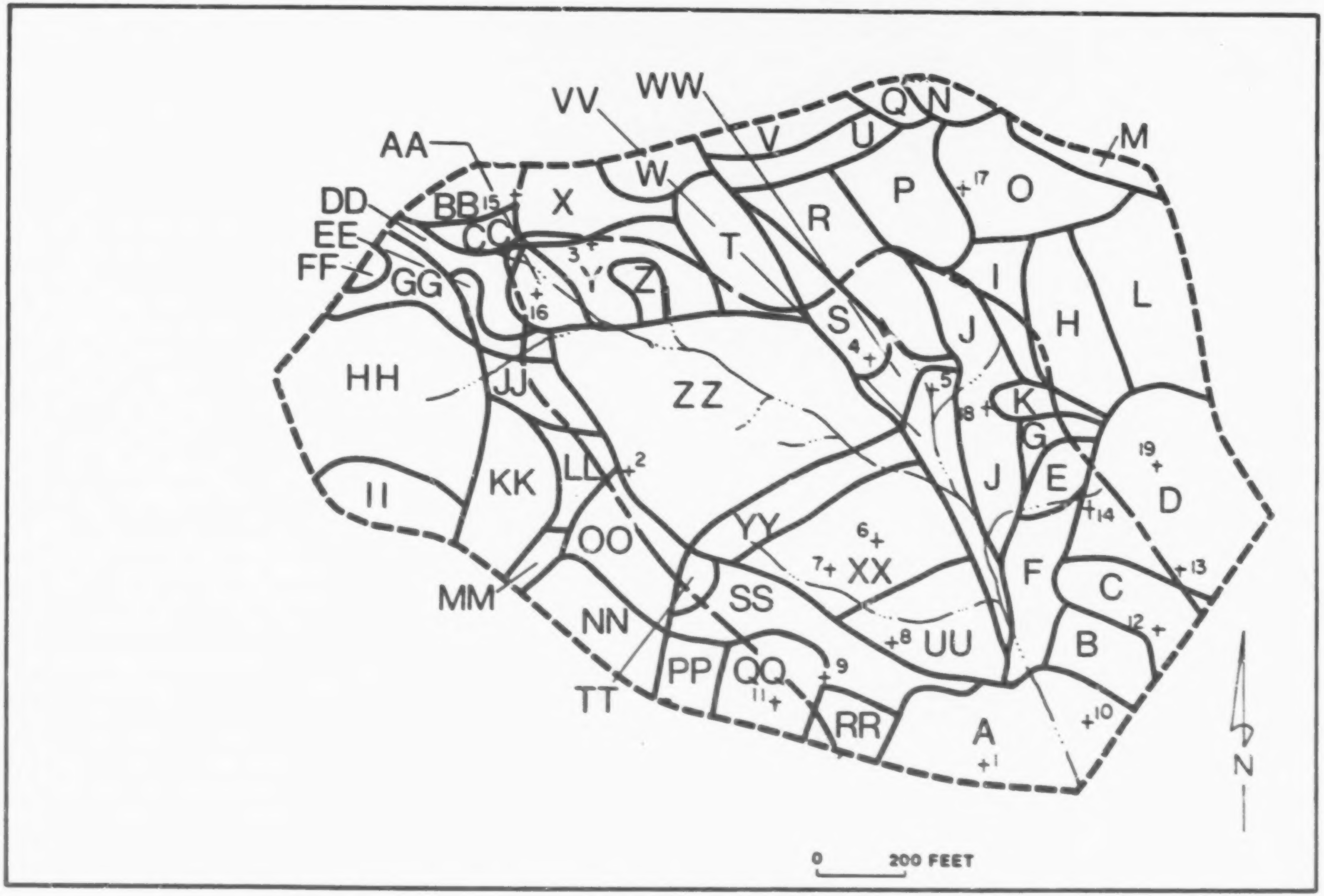
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Figure 21. Premining Overstory Vegetation Map for Watershed C06

Table 11. Key to Overstory Vegetation Map for Site C06 (BA is basal area).

Mapping Unit ID	Description
A	Open ground, grassy (weir location)
B	Dogwood - 30 sq. ft./ac. BA
C	Tulip-poplar, Dogwood and Red Maple - 50 sq. ft./ac. BA
D	Red Oak - 30 sq. ft./ac. BA
E	Sassafras and Red Maple - 30 sq. ft./ac. BA
F	Dogwood - 30 sq. ft./ac. BA
G	Sassafras and Red Maple - 20 sq. ft./ac.BA
H	Aspen and Elm - 20 sq. ft./ac. BA
I	Red Maple - 20 sq. ft./ac. BA
J	Red Maple and Dogwood - 20 sq. ft.,/ac. BA
K	Red Oak - 20 sq. ft./ac. BA (all young reprod.)
L	Red Oak and White Oak - 20 sq. ft./ac. BA
M	Ailanthus and Elm - 60 sq. ft./ac. BA
N	Tulip-poplar and Red Oak - 60 sq. ft./ac. BA
O	Red Maple - 20 sq. ft./ac. BA
P	Tulip-poplar and Red Oak - 10 sq. ft./ac. BA
Q	Elm and Ailanthus - 50 sq. ft./ac. BA
R	Aspen and Dogwood - 50 sq. ft./ac. BA
S	Aspen and Dogwood - 60 sq. ft./ac. BA
T	Aspen and Red Maple - 20 sq. ft./ac. BA
U	Red Oak, Tulip-poplar and some Hickory - 30 sq. ft./ac. BA

Table 11. (Cont'd) Key to Overstory Vegetation Map for Site C06.

Mapping Unit ID	Description
V	Red Maple and Aspen - 45 sq. ft./ac. BA
W	Red Maple, Black Tupelo and Cherry - 15 sq. ft./ac BA
X	Aspen, White Oak, Hickory - 40 sq. ft./ac BA
Y	Red Oak and Hickory - 40 sq. ft./ac. BA
Z	Aspen and Red Maple - 30 sq. ft./ac. BA
AA	Tulip-poplar - 60 sq. ft./ac. BA
BB	Sassafras - 50 sq. ft./ac. BA
CC	Aspen - 35 sq. ft./ac. BA
DD	Red Maple - 10 sq. ft./ac. BA
EE	Bramble and Briar (open area)
FF	Tulip-poplar - 60 sq. ft./ac. BA
GG	Red Maple and Aspen - 50 sq. ft./ac. BA
HH	Hickory, Tulip-poplar - 30 sq. ft./ac. BA
II	Aspen - 30 sq. ft./ac. BA
JJ	Sassafras - 20 sq. ft./ac. BA
KK	Aspen, Dogwood and Hickory - 60 sq. ft./ac. BA
LL	Tulip-poplar 30 sq. ft./ac. BA
MM	Cherry - 20 sq. ft./ac. BA
NN	Tulip-poplar - 40 sq. ft./ac. BA
OO	Hickory and Tulip-poplar - 30 sq. ft./ac. BA
PP	Red Maple and Dogwood - 20 sq. ft./ac. BA
QQ	Hickory and Tulip-poplar - 40 sq. ft./ac. BA

Table 11. (Cont'd) Key to Overstory Vegetation Map for Site C06.

Mapping Unit ID	Description
RR	Dogwood and Red Maple - 20 sq. ft./ac. BA
SS	Red Maple and Dogwood - 10 sq. ft./ac. BA
TT	Opening (annuals and perennials)
UU	Red Maple - 20 sq. ft./ac. BA
VV	Red Maple and Bramble - 10 sq. ft./ac. BA
WW	Opening (grasses)
XX	Tulip-poplar - 70 sq. ft./ac. BA
YY	Dogwood and Elm - 10 sq. ft./ac. BA
ZZ	Red Maple and Aspen (interspersed openings with bramble) - 10 sq. ft./ac. BA

Table 12. Summary of Cover Surrounding the Soil Moisture Access Tubes in Watershed C06.

Plot No.	Sawtimber (12" + dbh)[1] Net Volume Bd. Ft., (Doyle)	Pole Timber (6"-11" dbh) Net Volume Cords	Woody Reproduction (1"-5" dbh) Number stems	Ground Cover			
				Herbs %	Woody %	Duff %	Bare Soil and/or Rock %
1	0	0	2	55	15	30	0
2	0	1.13	4	45	12	43	0
3	0	2.15	11	25	25	35	15
4	0	0	4	19	8	47	26
5	0	0	11	82	6	8	4
6	31	2.07	4	30	16	44	10
7	80	7.85	3	13	8	54	25
8	0	.50	6	20	22	38	20
9	----------	----------	Plot Eliminated	----------	----------	----------	----------
10	0	.50	2	78	12	8	2
11	414	0	4	6	3	58	33
12	0	3.56	4	3	6	43	48
13	75	2.01	2	26	11	60	3
14	0	.50	4	50	30	5	15

Table 12. (Cont'd) Summary of Cover Surrounding the Soil Moisture Access Tubes in Watershed C06.

Plot No.	Sawtimber (12" + dbh)[1] Net Volume Bd. Ft. (Doyle)	Pole Timber (6"-11" dbh) Net Volume Cords	Woody Reproduction (1"-5" dbh) Number stems	Ground Cover			
				Herbs %	Woody %	Duff %	Bare Soil and/or Rock %
15	0	2.91	5	11	15	55	19
16	0	7.49	5	16	8	40	36
17	39	2.83	7	23	19	28	30
18	0	0	6	34	18	43	5
19	0	.99	14	35	24	37	4
Plot Average	35.5	1.92	5.44	32	14	38	16
Per Acre Average	354	34.5	544	32	14	38	16

[1] Diameter at breast height

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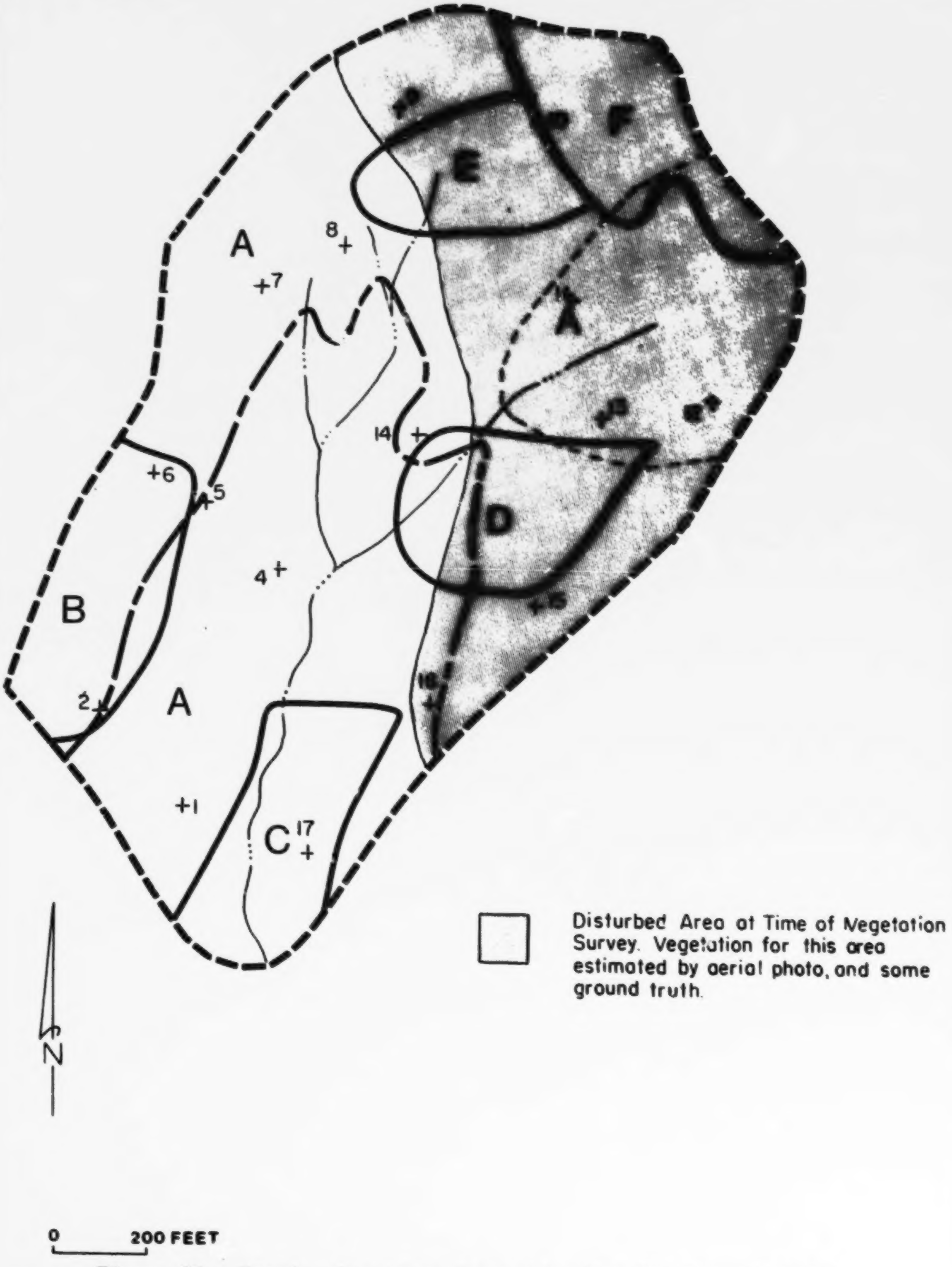
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Disturbed Area at Time of Vegetation Survey. Vegetation for this area estimated by aerial photo, and some ground truth.
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Figure 22. Preming Overstory Vegetation Map for Watershed M09

Table 13. Key to Overstory Vegetation Map for Site M09 (BA is basal area).

Mapping Unit ID	Description
A	Primarily grass and broadleaved herbs; small amounts of woody vegetation present.
B	Elm and Red Maple - 40 sq. ft./ac. BA
C	Elm and Red Maple - 70 sq. ft./ac. BA
D	Elm, Sycamore and Red Maple - 40 sq. ft./ac. BA
E	Red Oak and Tulip-poplar - 40 sq. ft./ac. BA
F	White Oak and Tulip-poplar - 60 sq. ft./ac. BA

Table 14. Summary of Cover Surrounding the Soil Moisture Access Tubes in Watershed M09.

Plot No.	Sawtimber (12" + dbh)[1]		Pole Timber (6"-11" dbh)		Woody Repro. (1"-5" dbh) No. Stems	Ground Cover			
	Gross Vol. Bd. Ft. (Doyle)	Net Vol. Bd. Ft. (Doyle)	Gross Vol. Cords	Net Vol. Cords		Herbs & Grasses %	Woody %	Duff %	Bare Soil and/or Rock %
1					Plot Eliminated				
2	0	0	0	0	0	85	5	0	10
3	0	0	0	0	0	95	0	0	5
4	0	0	0	0	0	95	0	0	5
5	0	0	0	0	0	85	5	0	10
6	0	0	0	0	0	70	20	0	10
7	0	0	0	0	0	90	0	10	0
8-16					Plots Eliminated				
17	3880	2465	3.7	3.7	4	15	25	35	25
Per Acre Avg.	554	352	0.53	0.52	57	77	8	7	8

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[1] Diameter at breast height

volume was 76 board feet per acre. Gross volume of pole timber was 0.04 cords per acre and net volume 0.03 cords per acre. Only 3 of 11 sample points were stocked with woody reproduction, with an average of 173 stems per acre. Dominant species in this group were black cherry, ash, and ailanthus. Ground cover for the area was quite variable, including herbaceous vegetation ranging from 40 to 100 percent, woody vegetation 0 to 9 percent, duff cover 0 to 55 percent, and bare soil and/or rock from 0 to 14 percent. Average type distributions were: herbs 87 percent; woody 2 percent; duff 10 percent; and bare 1 percent.

The vegetation map, its key, and the summary of cover surrounding the soil moisture access tubes are shown in Figure 23 and Tables 15 and 16, respectively.

5. Watershed J08

The watershed had a southeasterly aspect. Results from the timber cruise showed a large percentage of cull percent within the standing trees primarily due to overmaturity and growth form. Gross board feet volume was 289 board feet per acre and net volume was 241 board feet per acre. The major sawtimber species were black locust, black cherry, American elm, osage orange, and black walnut. Pole timber trees showed less cull with an acre average of 7.8 cords for gross and 7.6 for net. Major pole timber species were black cherry, osage orange, black locust, and white ash. Woody reproduction species included white ash, cherry, black locust, oak, osage orange, and elm.

Herbaceous vegetation cover ranged from 6 to 63 percent, woody cover from 0 to 5 percent, duff cover from 0 to 77 percent, and bare soil and rock from 0 to 82 percent. Average type distributions were: 35 percent herbs, 4 percent woody, 42 percent duff, and 19 percent soil and rock.

The vegetation map, its key, and the summary of cover surrounding the soil moisture access tubes are shown in Figure 24 and Tables 17 and 18, respectively.

6. Watershed A06

The A06 study area consisted of many diverse conditions, with aspects ranging from east to west. The entire watershed had a southerly aspect. Vegetation was quite diverse, ranging from upland oak-hickory types to planted stands of white and red pine. Vegetation within the area was of a discontinuous cover form. At the northern tip of the watershed, black locust was dominant where a recent disturbance from the harvesting of trees for posts had occurred. Other small areas within the watershed showed recent interruption, as a result of cutting for pulpwood without removal.

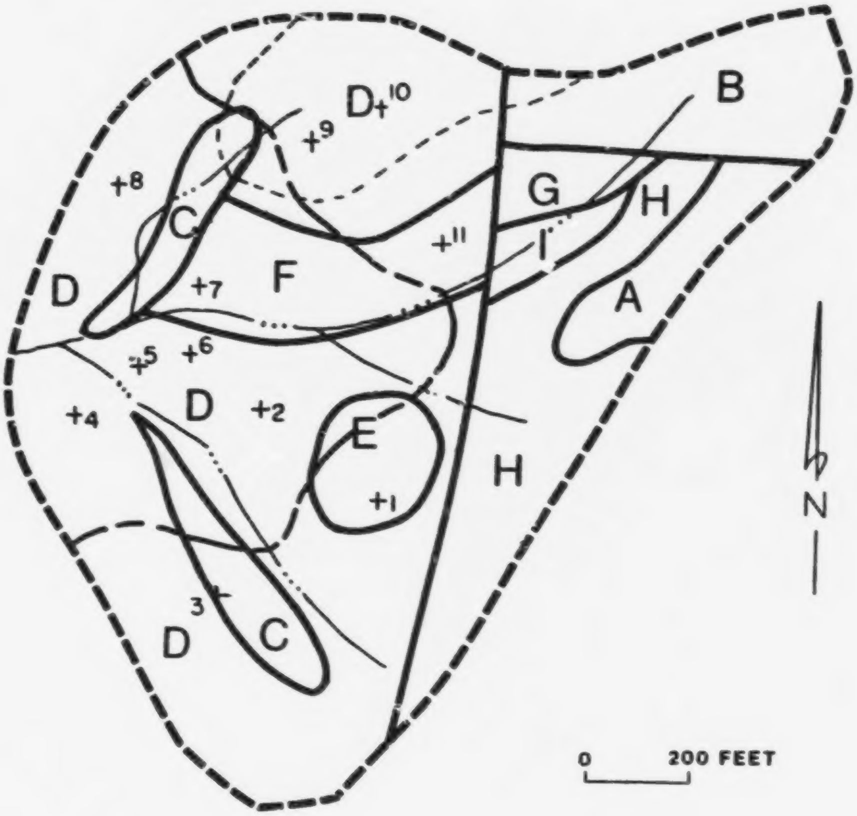
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Figure 23. Premining Overstory Vegetation Map for Watershed J11

Table 15. Key to Overstory Vegetation Map for J11 (BA is Basal area).

Mapping Unit ID	Description
A	Briars and herbaceous material, 1 to 2 feet tall
B	Cornfield with grass border strip
C	Creek/gully: Red Maple, Willow and Black Locust (grazed) - 10-20 sq. ft./ac. BA
D	Grass pasture (grazed)
E	Ailanthus, up to 12" dbh (grazed) - 70 sq. ft./ac. BA
F	Black Locust, grass surface vegetation (grazed) - 70 sq. ft/ac. BA
G	Young woody reproduction: Ash, Red Maple and Black Cherry - 60-70 sq. ft./ac. BA
H	Scattered mature Black Locust, Ash, Red Maple and Black Cherry - 30-40 sq. ft./ac. BA
I	Ash, Red Maple and Black Cherry (along gully) - 60 sq. ft./ac. BA

Table 16. Summary of Cover Surrounding the Soil Moisture Access Tubes in Watershed J11.

Plot No.	Sawtimber (12" + dbh)[1] Net Volume Bd. Ft. (Doyle)	Pole Timber (6"-11" dbh) Net Volume Cords	Woody Reproduction (1"-5" dbh) Number Stems	Ground Cover			
				Herbs %	Woody %	Duff %	Bare Soil and/or Rock %
1	344	.025	4	40	5	55	0
2	110	.335	5	77	9	0	14
3	0	0	0	100	0	0	0
4	0	0	0	100	0	0	0
5	0	0	0	100	0	0	0
6	1260	0	0	100	0	0	0
7	100	.427	0	100	0	0	0
8	0	0	0	100	0	0	0
9	0	0	0	100	0	0	0
10	0	0	0	100	0	0	0
11	0	.032	10	43	6	51	0
Plot Average	164	.075	1.73	87	2	10	1
Per Acre Average	76	0.03	173	87	2	10	1

[1] Diameter at breast height

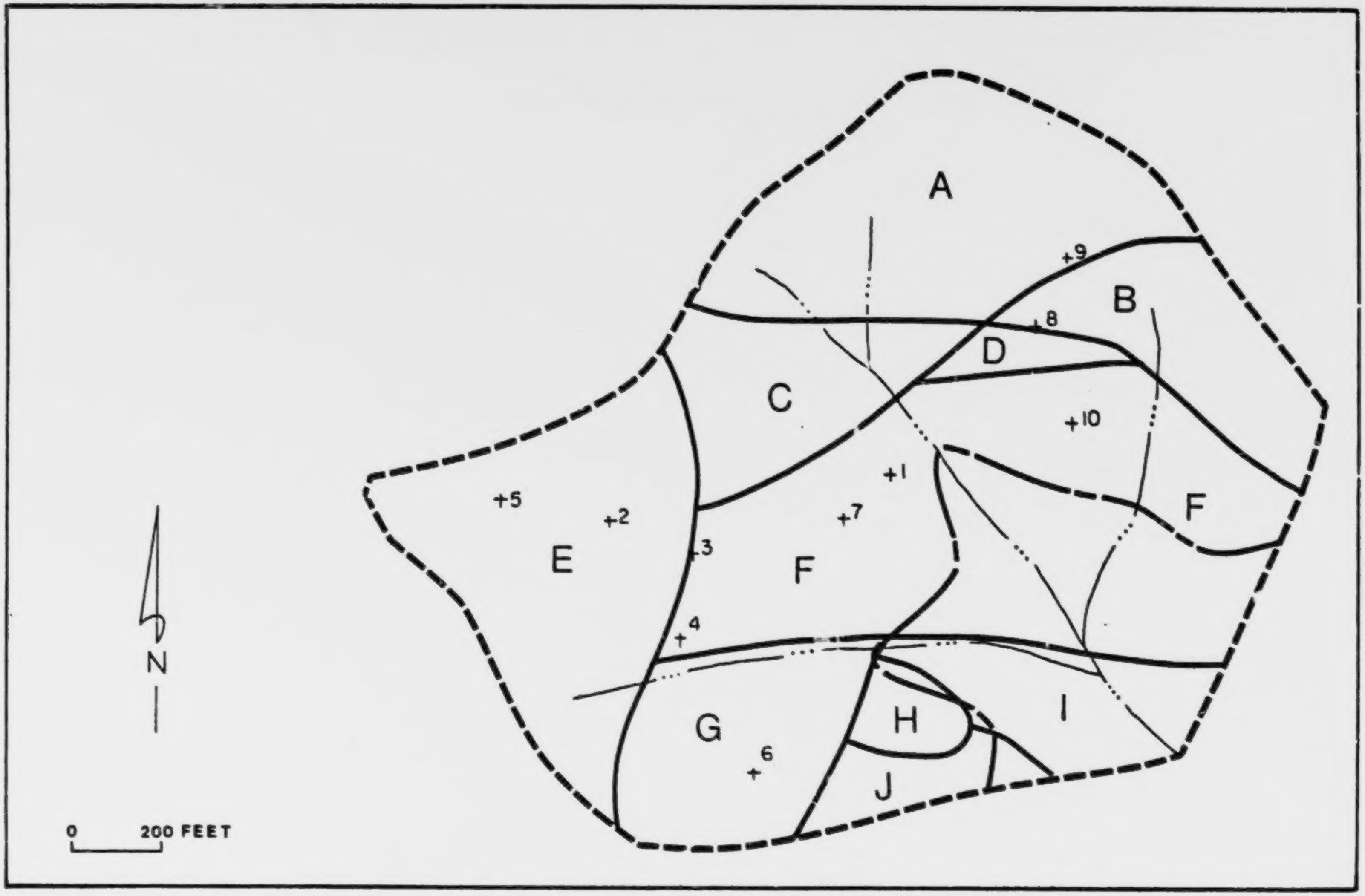
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Figure 24. Premining Overstory Vegetation Map for Watershed J08

Table 17. Key to Overstory Vegetation Map for J08 (BA is basal area).

Mapping Unit ID	Description
A	Black Cherry - 55 sq. ft./ac. BA
B	Black Locust - 50 sq. ft./ac. BA
C	Black Cherry, Osage Orange and Elm - 45 sq. ft./ac. BA
D	Black Cherry - 10 sq. ft./ac. BA
E	Black Cherry - 10 sq. ft./ac. BA
F	Black Cherry, Elm and Black Locust - 40 sq. ft./ac. BA
G	Black Cherry, Black Locust and Elm - 100 sq. ft./ac. BA
H	Black Cherry and Black Locust - 30 sq. ft./ac. BA
I	Black Cherry and Elm - 80 sq. ft./ac. BA
J	Black Locust and Elm - 30 sq. ft./ac. BA

Table 18. Summary of Cover Surrounding Proposed Soil Moisture Access Tubes in Watershed J08.

Plot No.	Sawtimber (12"+ dbh)[1] Net Volume Bd. Ft. (Doyle)	Pole Timber (6"-11" dbh) Net Volume Cords	Woody Reproduction (1"-5" dbh) Number Stems	Ground Cover			
				Herbs %	Woody %	Duff %	Bare Soil and/or Rock %
1	0	0.060	3	48	4	35	13
2	0	0.160	2	37	5	58	--
3	187	0.556	0	45	--	65	--
4	484	0	2	30	--	70	--
5	0	0	0	63	1	35	1
6	119	0.151	2	20	3	77	--
7	0	0	3	58	5	20	17
8	0	0	0	21	--	--	79
9	0	0.030	7	6	4	8	82
10	410	0.381	2	25	4	71	--
Plot Average	120	0.112	2	35	4	42	19
Per Acre Average	241	7.6	2	35	4	42	19

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[1] Diameter at breast height

Average total sawtimber volume was 18,025 board feet per acre. A percentage of cull was present in many trees, leaving a net volume of 15,670 board feet per acre. The major sawtimber species were tulip-poplar, red oak, white oak, red pine, and white pine. Pole timber gross volume was 27.0 cords per acre and net volume was 26.5 cords per acre. Major pole-sized species included red pine, tulip-poplar, and black locust.

Woody reproduction was quite variable throughout the area, with an average of 594 stems per acre. Species in this group included dogwood, tulip-poplar, sugar maple, black maple, red maple, black cherry, and others. Ground cover for the watershed was quite variable, including herbaceous vegetation ranging from 2 to 56 percent, woody vegetation from 1 to 42 percent, duff cover from 38 to 86 percent, and bare soil and/or rock from 0 to 18 percent. Average type distributions were: herbs 3 percent; woody 16 percent; duff 68 percent; and bare 3 percent.

The vegetation map, its key, and the summary of cover surrounding the soil moisture access tubes are shown in Figure 25 and Tables 19 and 20, respectively.

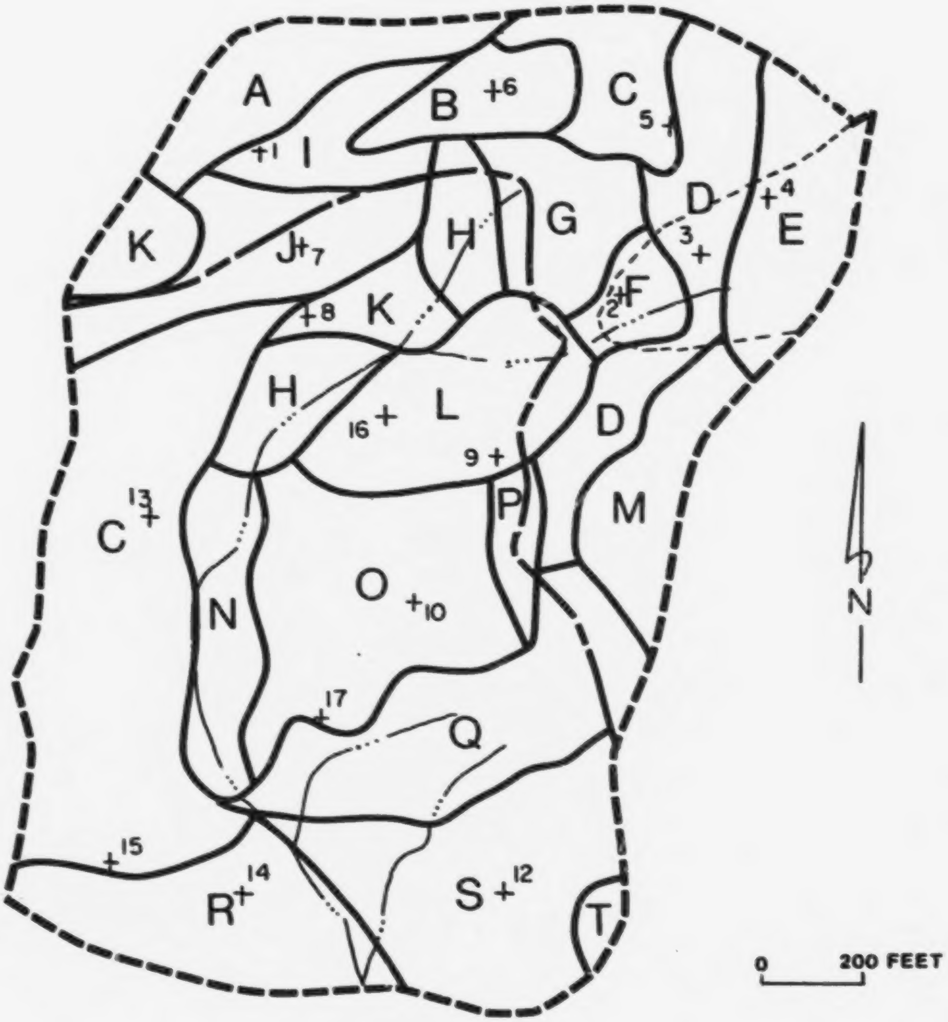
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Figure 25. Overstory Vegetation Map for Unmined Watershed A06

Table 19. Key to Overstory Vegetation Map for A06 (BA is basal area).

Mapping Unit ID	Description
A	Black Locust and herbaceous vegetation - 40 sq. ft./ac BA
B	White Pine - 90 sq. ft./ac BA
C	White Pine and Tulip-poplar - 70 sq. ft./ac. BA
D	Tulip-poplar, Red Oak and White Oak - 50 sq. ft./ac. BA
E	Tulip-poplar, Chestnut Oak and Red Oak - 40 sq. ft./ac. BA
F	Tulip-poplar and White Oak - 50 sq. ft./ac. BA
G	Tulip-poplar and White Oak - 40 sq. ft./ac. BA
H	Briars, bramble, scattered Black Locust and Red Maple (dense grapevine and briars present) - 20 sq. ft./ac. BA
I	Tulip-poplar - 50 sq. ft./ac. BA
J	White Pine - 70 sq. ft./ac. BA
K	White Pine (dominant) and Black Locust - 60 sq. ft./ac. BA
L	Red Pine - 85 sq. ft./ac. BA
M	Tulip-poplar, Hickory and Black Locust - 60 sq. ft./ac. BA
N	Ash and Tulip-poplar with briars and bramble - 50 sq. ft./ac. BA
O	Young stand of Black Cherry, Red Maple and Dogwood (dense) - 40 sq. ft./ac. BA
P	Sassafras, Red Maple, Red Oak, Dogwood, Black Cherry, Ash and Black Locust pioneer succession after recent interruption - 30 sq. ft./ac. BA
Q	Red Oak and Hickory - 40 sq. ft./ac. BA
R	Tulip-poplar, Black Locust and Black Cherry - 50 sq. ft./ac. BA
S	Larger stand of White Oak and Red Oak - 80 sq. ft./ac. BA
T	White Pine - 40 sq. ft./ac. BA

Table 20. Summary of Cover Surrounding Soil Moisture Access Tubes in Watershed A06.

Plot No.	Sawtimber (12" + dbh)[1] Net Volume Bd. ft. (Doyle)	Pole Timber (6"-11" dbh) Net Volume Cords	Wood Reproduction (1"-5" dbh) No. of stems 1/100th acre	Ground Cover			
				Herbs %	Woody %	Duff %	Bare Soil and/or Rock %
1	0	.801	4	52	10	38	0
2	178.979	1.808	5	4	17	79	0
3	201.459	.681	5	2	5	86	7
4	316.827	.317	6	2	6	85	7
5	152.207	.521	8	12	5	65	18
6	730.091	1.422	2	4	11	85	0
7	459.943	.858	1	56	1	43	0
8	445.893	.262	7	5	14	81	0
9	301.159	1.693	2	9	40	51	0
10	0	0	16	10	42	48	0
11	363.860	.690	10	8	21	71	0
12	182.236	.606	10	6	16	60	18
13	544.933	1.213	3	6	19	75	0
14	679.032	.380	0	23	21	56	0
15	394.420	.421	2	14	7	79	0

Table 20. (Cont'd) Summary of Cover Surrounding Soil Moisture Access Tubes in Watershed A06.

Plot No.	Sawtimber (12" + dbh)[1] Net Volume Bd. ft. (Doyle)	Pole Timber (6"-11" dbh) Net Volume Cords	Wood Reproduction (1"-5" dbh) No. of stems 1/100th acre	Ground Cover			
				Herbs %	Woody %	Duff %	Bare Soil and/or Rock %
16	294.412	1.118	8	9	9	82	0
17	20.455	0	12	6	15	79	0
Plot Avg.	309.759	.752	5.94	13	16	68	3
Per Acre Avg.	15.670	26.5	5.94	13	16	68	3

[1] Diameter at breast height

III. SURFACE-WATER HYDROLOGY

A. Experimental Design and Procedures

1. Introduction

In order to adequately evaluate the hydrology of watersheds, weather and surface and subsurface hydrologic data must be collected. Data required are those that can be used to numerically describe the components of the hydrologic cycle, depicted in Figure 26, either directly or indirectly. Also for modeling of watershed hydrology and water quality, spatial and temporal numerical descriptions of the components are necessary. The hydrologic data collection system for each watershed was designed to meet these needs.

The four selected study watersheds that are to experience surface mining are to be studied in their natural condition and through the mining and reclamation phases, to investigate the effect of surface mining on hydrology and water quality. The premining phase was to last approximately one year, but a one-year period is too short to show how an individual watershed responds to varying weather conditions (i.e., dry years, wet years, extreme events, etc.). Therefore, data from each study watershed and the control watershed, which has a long hydrologic record, will be utilized to develop (or adapt) a hydrologic model that describes and predicts the hydrologic behavior of each study watershed under varying inputs.

Because of the five-year limit for the project, it was necessary to restrict either the premining or postmining phase; the mining phase was expected to take an estimated 8 to 12 months. The decision was made to restrict the premining phase so that more time would be allowed for the watersheds to approach an equilibrium condition following reclamation.

2. Weather Data

Weather instruments were installed at the C06, M09, and J11 sites (instrumentation existed near the A06 site) to record the important parameters of precipitation, temperature, relative humidity, wind speed, and solar radiation. Precipitation is the basic input and driving force of the hydrologic system; temperature determines the form of precipitation and, also, along with humidity, wind, and solar radiation affect the amounts of evapotranspiration; and temperature and solar radiation exert major control over the rate of snowmelt.

A typical weather station is shown in Figure 27. The location of the stations for Watersheds C06, M09, and J11 are shown on the respective topographic maps (Figures 2, 3, and 4). The weather data obtained at the J11 site will be used for the J08 site (located 5 miles to the

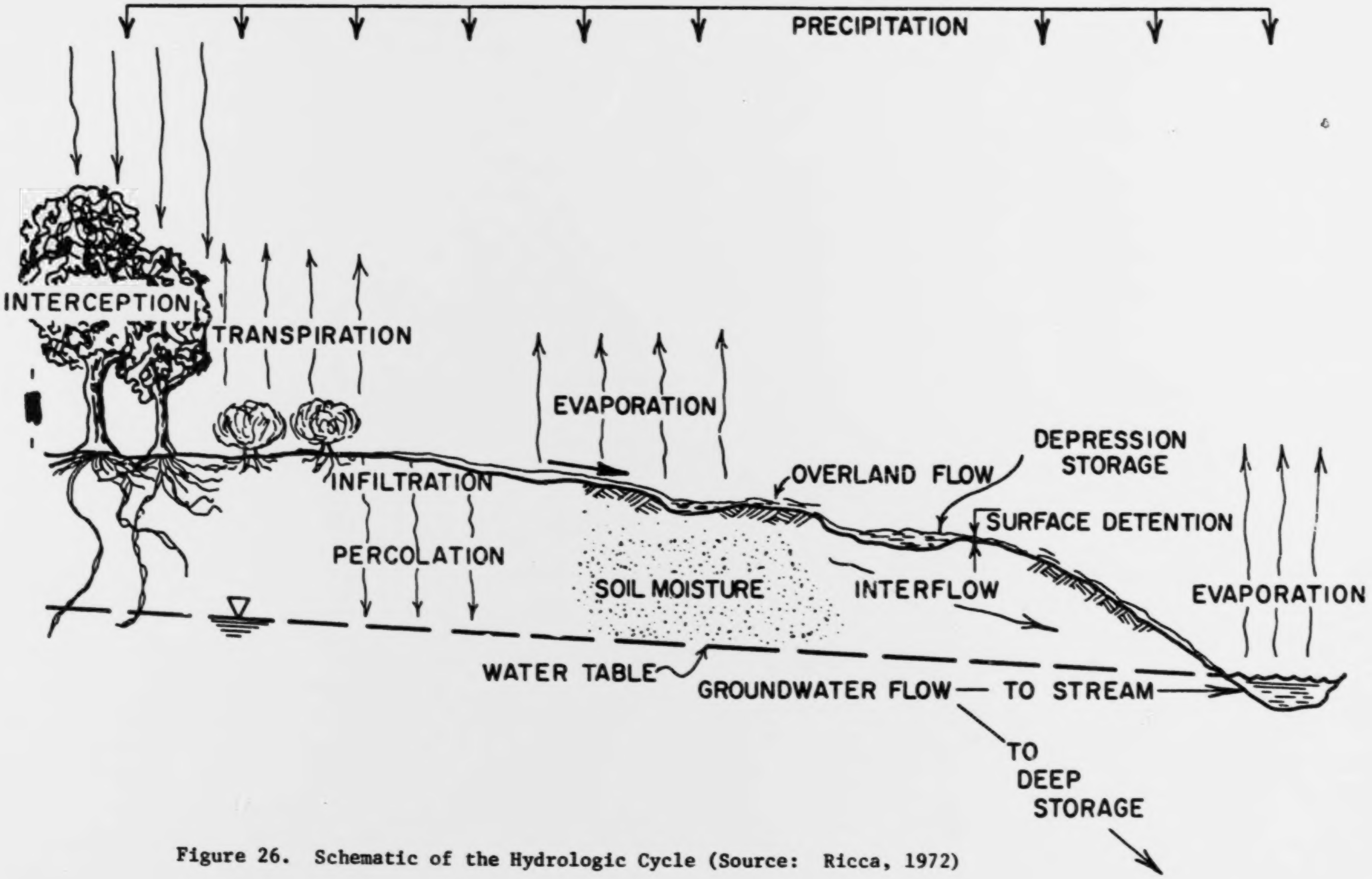
PRECIPITATION
INTERCEPTION
TRANSPIRATION
EVAPORATION
DEPRESSION STORAGE
OVERLAND FLOW
INFILTRATION
SURFACE DETENTION
PERCOLATION
SOIL MOISTURE
INTERFLOW
EVAPORATION
WATER TABLE
GROUNDWATER FLOW — TO STREAM
TO DEEP STORAGE

Figure 26. Schematic of the Hydrologic Cycle (Source: Ricca, 1972)

Figure 27. Typical Weather Station (C06 Site)

east-northeast), except for precipitation which will be measured in or near Watershed J08. For Watershed A06, precipitation was measured by a gage just outside the watershed, by dual gages located 4,000 feet to the northeast, and by snow boards in the wooded watershed area. The other weather elements were measured at a site about 3,000 feet to the east-northeast of the center of the watershed.

Precipitation was measured by use of two standard National Weather Service weighing bucket gages--one unshielded and one shielded with a rigid Alter type shield. Their orifices were 2 meters above the ground. The gages are shown in the foreground of Figure 27. A formula was derived by Hamon (1972) to use the measured precipitation from both gages in order to compute precipitation corrected for catch deficiencies under windy conditions. The ratio of the computed total to the unshielded total is multiplied by the unshielded breakpoints to give a time trace of computed breakpoint precipitation. For rainfall the differences are small between the unshielded and computed values, with the computed totals being slightly higher than unshielded totals most of the time. Large differences exist between the two totals for precipitation falling as snow because of the effect of wind on snowfall catch.

Temperature and relative humidity data were obtained from a drum-type hygrothermograph placed in a standard weather screen as shown in Figure 27.

Data on incident solar radiation were collected near the A06 site from an Epply Pyranometer by use of an analogue recorder with an attached integrator. Both net and incident radiation were obtained at the J11 site by an integrating-printing instrument. Data loggers will be used to obtain solar radiation and other weather elements at the C06 and M09 sites.

Wind data were obtained by a 3-cup anemometer with recording of wind-run on a mechanically driven drum. For every mile of wind passing the anemometer, a pen marked on the drum. The anemometer is shown in the middle of Figure 27.

3. Snow and Frozen Soil

Snow and frozen soil are important factors in wintertime hydrology. Snow can be considered as delayed rainfall; water is released, during warmer days, from snowpack storage that accumulated from prior precipitation. Frozen soil changes the infiltration characteristics of a watershed. This usually causes most of the rainfall or snowmelt to flow directly to a channel.

Snow and frozen soil data were collected periodically at various sampling points and at every soil mositure access tube. A complete set of data included location, snow depth, equivalent water content, an estimate of snow distribution, the location of the layer of frozen soil, and other observer comments.

4. Soil Moisture

Soil moisture content (storage) has an important effect on the hydrologic cycle (Figure 26) as it affects the rate of infiltration and ground-water recharge. Also, it is the source of water for most watershed evapotranspiration. Soil moisture storage amounts are affected by soil type, soil physical characteristics, vegetative cover, and topography.

A network of access tubes to accommodate a neutron probe for measurement of soil moisture was established in each watershed (see section on soils under Description of Study Sites). At the time of access tube installation, the only data available were the soil surveys and topographic maps; the vegetation surveys had not been made. A preliminary soil moisture network was designed using available data, and then vegetation was considered in modifying the preliminary network.

Soil moisture was measured every 1 or 2 weeks to a depth of 51 inches--the gravimetric method was used to determine soil moisture in the top 9 inches, and the neutron probe method for the remaining depth at 6-inch increments.

The gravimetric sampler (a 9-inch long cylinder attached to a frame) and the neutron probe are shown in Figure 28. Access tubes for the neutron probe were made of 1.9-inch diameter aluminum irrigation tubes. They extended from 3 inches above the soil surface to 52 inches below the surface. The bottom inch in the tube was sealed with hydraulic cement to prevent water from entering the tube. The top was sealed with a rubber stopper and covered with a can to prevent water from entering and animal molestation. A cloth bag containing a dessicant was suspended from the stopper to prevent moisture from accumulating on the tube walls. Dessicant bags were replaced when necessary.

The neutron probes were calibrated by using saturated and dry soils in separate 55-gallon drums with access tubes in their centers. These two extreme points defined the linear calibration curve.

5. Infiltration

Water entering the soil by the infiltration process along with that retained by interception and surface detention determines the amount of surface runoff from rainfall and snowmelt. Runoff from watersheds represents an integrated response of the watershed area to precipitation input. Such information is valuable in assessing the hydrologic response of the particular watershed but is of limited applicability to a dissimilar area, particularly where surface mining is involved.

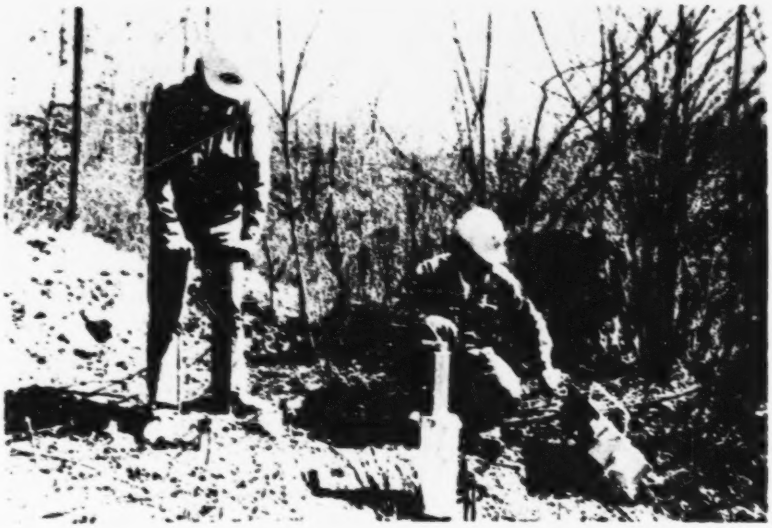

Figure 28. Soil Moisture Measuring Equipment (Gravimetric Samples on Left; Neutron Probe Apparatus on the Right)

A standard method to establish infiltration characteristics of soils is by use of an infiltrometer. A portable rainfall simulator-infiltrometer with unique capabilities for studying infiltration and hydraulic properties of soils (Jeppson, 1975) was used to measure infiltration.

The 6 by 6 foot infiltrometer, pictured in Figure 29, 30, and 31, has the capacity of applying water at rates from 0.1 to 8.0 inches per hour measured by flow meters (Figure 29) for each of the six 2 by 3 foot modules. Water drop sizes are controlled by the velocity of air flowing through orifices (3 inches on center) in which capillary needles are placed. By the use of two sets of modules containing different size needles, the mean drop size diameter of natural rainfall can be duplicated for intensities up to 4 inches per hour. With the flow modules suspended at a height of 8 feet, the kinetic energy of the simulated rainfall is about 75 percent of natural rainfall.

To collect surface runoff, a three-sided metal frame was driven to a depth of 8 to 12 inches into the soil. On the open downslope side, a wooden cut-off wall (the top edge shaped to conform with the surface) was placed at an equal depth into the ground and a runoff collector attached (Figure 30). Runoff is transferred from the attached collector trough to a tank by a vacuum system and measured with a water stage recorder (Figure 31). A fiber reinforced plastic curtain is used to enshroud the rainfall simulator for protection from the wind.

6. Spring Discharge

Springs situated on the outcrop of the study coal seams in Watersheds C06 and M09 were developed to measure discharge and collect water quality samples. A trench was dug to the coal underclay and a 3-inch perforated PVC pipe was installed. Then the trench was partially backfilled with gravel, and finally backfilled with the original soil. Since the land surface at the outcrop was to be disturbed, the water was conveyed downslope by PVC pipe beyond the estimated toe of the spoil bank and measured in a protected and coated 0.75-ft. HS-flume. The A06 site had an existing spring developed near the outcrop of the No. 4 coal. This spring is instrumented with a 90° V-notch weir. The locations of the springs and measuring sites are shown in Figures 2, 3, and 6.

7. Runoff

A runoff hydrograph is basic to analytical watershed hydrology. It quantitatively pictures drainage area response to a precipitation input. As such, it is extremely important to computer modeling of watersheds, because the difference between recorded and simulated hydrographs is the measure of the success of a model.

In addition to the four principal watersheds to be used for monitoring hydrology and water quality, three small sub-watersheds

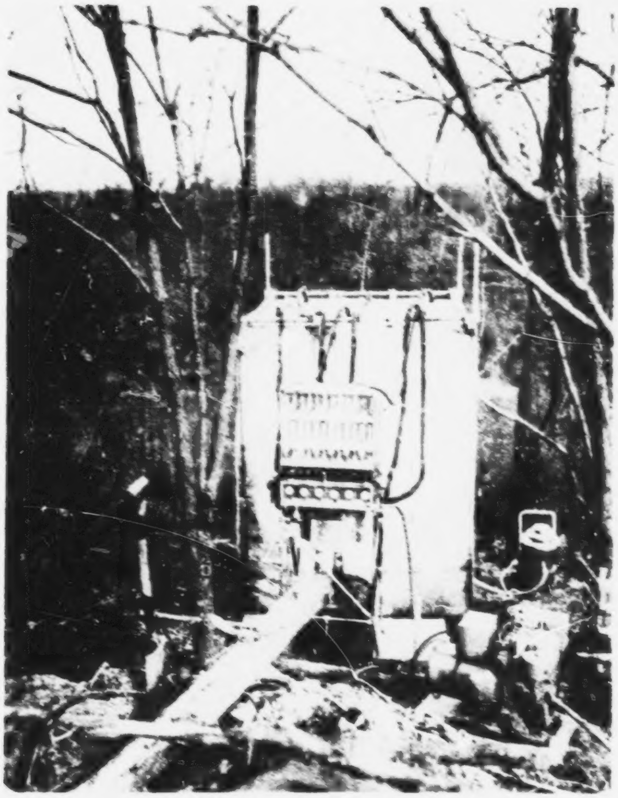

Figure 29. Rainfall Simulator-Infiltrometer Showing Water and Air Flow Control Unit (Site C06)

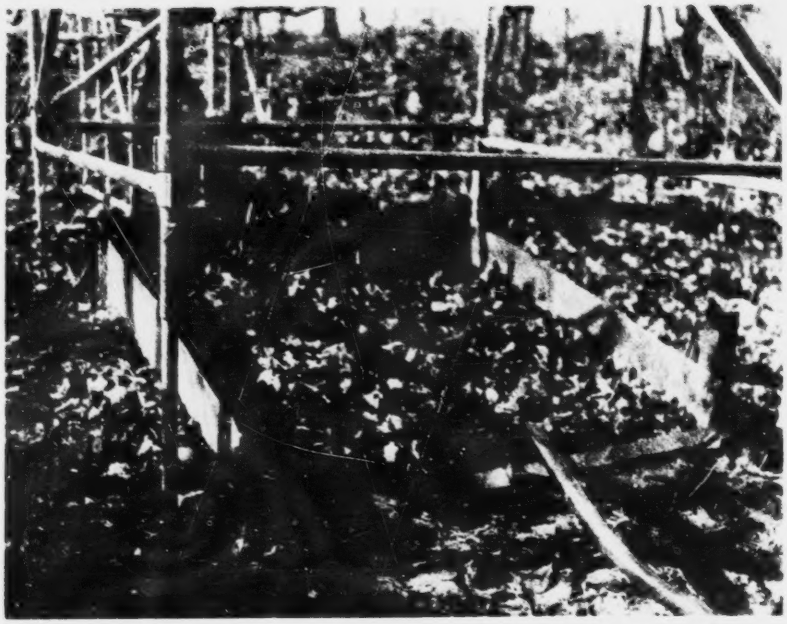

Figure 30. Runoff Collection System for Rainfall Simulator-Infiltrometer (Site C06)

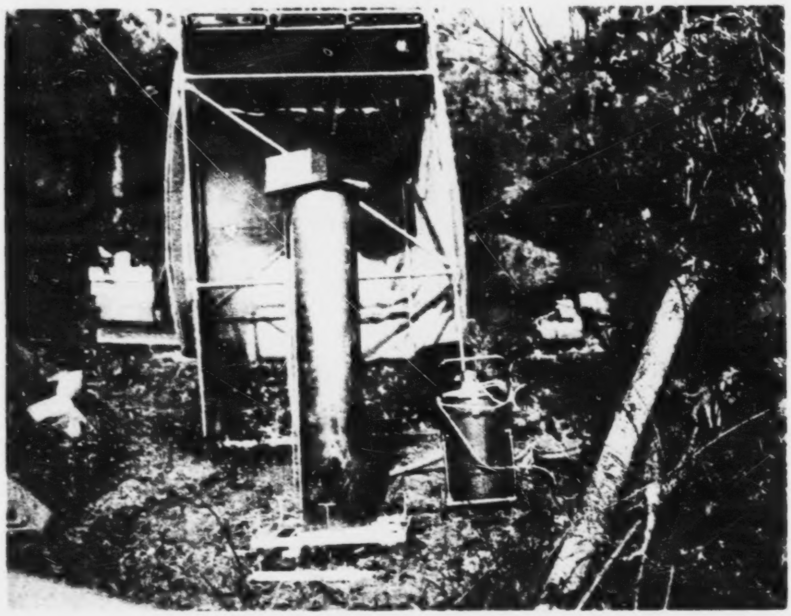

Figure 31. Collection Tank for Measuring Runoff from Rainfall Simulator-Infiltrometer (Site C06)

(designated SWS) for measuring runoff were put into operation. These small watersheds are shown in Figures 3, 4, and 6. The designations and areas of the small watersheds are given in Table 21.

Table 21. Small Watershed Areas

Site ID	Area (Ac.)
M09 - SWS	7.0
J11 - SWS	3.5
A06 - SWS	2.2

Runoff data were collected by use of four types of measuring devices: H-flumes, drop-box weirs, a broad-crested V-notch weir, and a Parshall flume. The measuring devices used at each site are listed in Table 22.

The choice of runoff measuring devices was based on the heavy sediment loads that would be carried by runoff water during the mining and early reclamation periods. Traditional approaches of using V-notch weirs and H-flumes were considered to be inadequate since the study sites would be unattended for several days at a time and the sediment loads expected would invalidate the ratings for these devices. The drop-box weir (Johnson et al, 1966), designed to pass large quantities of sediment without affecting the rating curve was selected for use on the watersheds. Because of the low sediment loads in the premining phase, temporary H-flumes were also used until drop-box weirs could be fabricated. The broad-crested V-notch weir at A06 was left intact; no sediment problem was expected because the watershed would not be mined.

A typical drop-box weir, with labeled components, is shown in Figure 32. The weir was designed to concentrate flows at all flow rates so as to make the weir self cleaning. At low flow, the water is diverted by the backwall toward the low flow chutes where it concentrates just above the V-notch section. At higher flows, water flows over the side weirs and concentrates the flows more upstream in the box. At even higher discharge, water flows over the back wall, as well as the side weirs, causing great turbulence which results in keeping the weir free of sediment. At flows in excess of the box capacity, the water is also discharged over the lower-sloped upper V-notch. A drop-box weir functioning during a runoff event is shown in Figure 32.

In computing discharge from head measurement in the weir, the height of the water is measured in two places: in the lower V-notch for low flows, and along the upper V-notch wall for high flows. The

Table 22. Summary of Runoff Measuring Devices Used on the Study Watersheds

Site	Runoff Measuring Device
C06	
Outlet	2.5' H-flume prior to Aug. 18, 1976 1.6' Drop-box weir after Aug. 18, 1976
M09	
Outlet	1.6' Drop-box weir
Small WS	3.0' H-flume
J11	
Outlet	2.5' H-flume (to be replaced by drop-box weir before mining begins)
Small WS	0.8' Drop-box weir
A06	
Outlet	Broad-crested V-notch weir
Small WS	0.5' Parshall flume

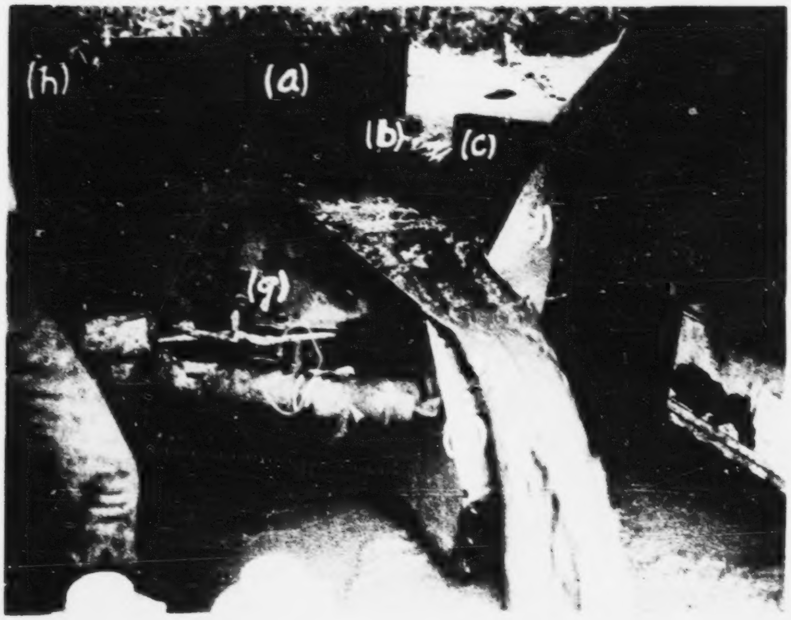

Figure 32. Drop-Box Weir in Operation with Components as Designated: a) Back Wall, b) Upper and Lower Side Weirs, c) Low Flow Concentrating Chute, d) Lower V-Notch Section, e) Low Flow Sediment Trap, f) Low Flow Intake Pipe to Stilling Well, g) Water Quality Sample Access, and h) Upper V-Notch

lower V-notch measuring section is equipped with a sediment trap below a slot in the V-notch, with an intake pipe to the stilling well. The upper V-notch measuring point is shown in Figure 33 and operates on the same principle as the lower V-notch, except the access hole is in the side wall of the weir.

Installation of all weirs was basically the same; a trench was dug perpendicular to the stream channel to a relatively impervious layer, and a concrete footing and cutoff wall were poured. The cutoff wall was designed with an opening for attaching the flow measuring device and extensions on both sides to decrease the hydraulic gradient of unmeasured sideflow. In addition, an energy dissipating pad with roughness elements was constructed at the larger weir installations (Figure 33). Photographs of the construction prior to weir installation are shown in Figures 34 and 35. An H-flume installation at the M09 small watershed is shown in Figure 36, and the broad crested V-notch weir at the A06 site is shown in Figure 37.

The water stage or gage height was obtained at each weir installation by use of a float operated recorder. Breakpoint data were obtained from the recorder traces and the discharge obtained by the use of stage-discharge relationships.

The C06, M09, and A06 outlet sites were instrumented with Coshocton vane type, automatic water quality (composite) samplers. The sampler is a rotating tear-shaped vane that passes under a constant discharge (pumped) outfall moved by the stilling well float. The basic theory and design of the sampler was described by Edwards et al, (1976). The sampler intake on the drop-box is shown in Figure 32.

Chickasha samplers (Miller et al, 1969) were installed at the C06 and M09 sites to obtain discrete samples at time intervals throughout the hydrograph. These samples were analyzed for both sediment and chemical water quality. Grab samples were also obtained at all sites for these purposes.

B. Results and Discussion

1. Introduction

The record periods for each parameter for each watershed (Table 23) varied as instruments were installed and mining progressed. The premining phase ended when the watershed hydrology was changed by removal of trees and/or by building of roads. The premining records for C06 and M09 are less than 1 year in length. The J11 site has not yet been mined. Because J08 has not been instrumented, the premining period for this watershed has not begun, except for the collection of some ground-water data. The A06 site can be considered to be in a continuous premining condition.

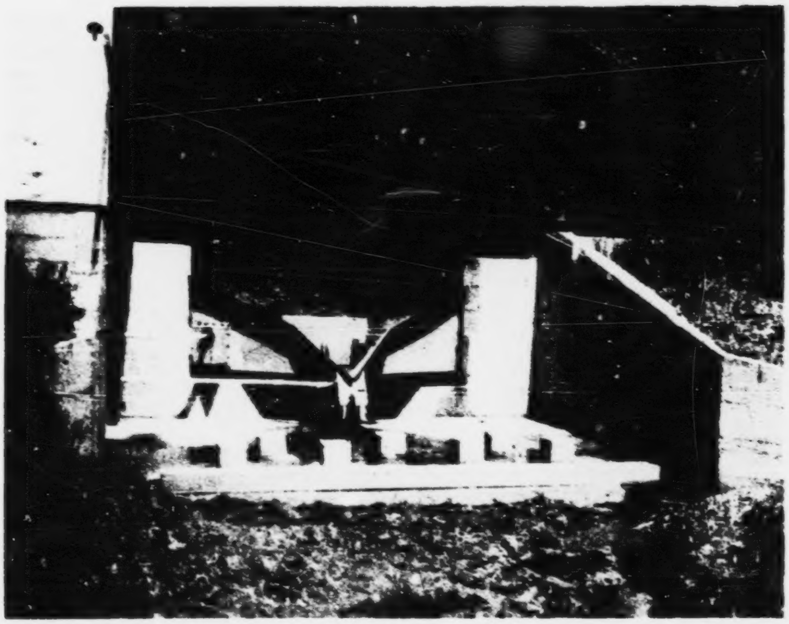

Figure 33. Typical Drop-Box Weir Installation (M09 Site)

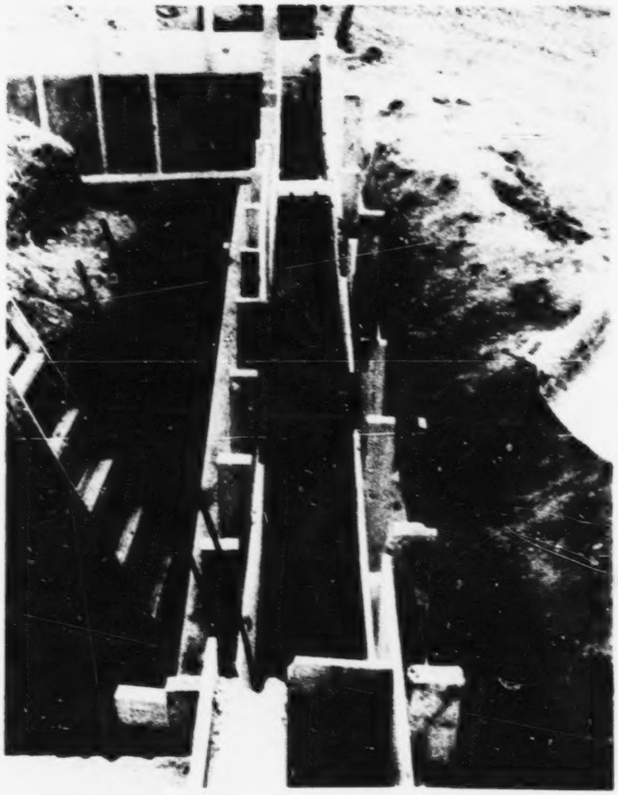

Figure 34. Typical Cut-Off Wall Under Construction Showing Forms and Reinforcing Rods

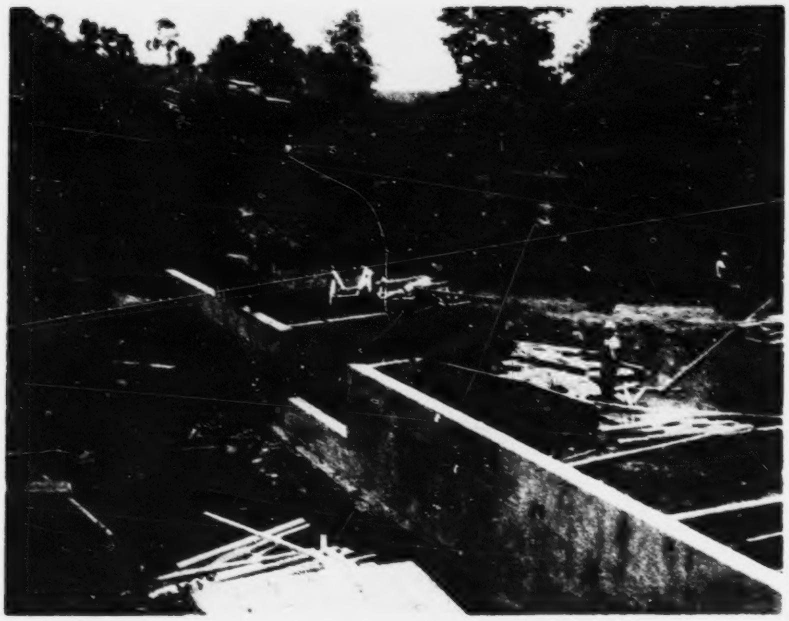

Figure 35. Completed Cut-Off Wall Showing Opening for the Flow Measuring Device

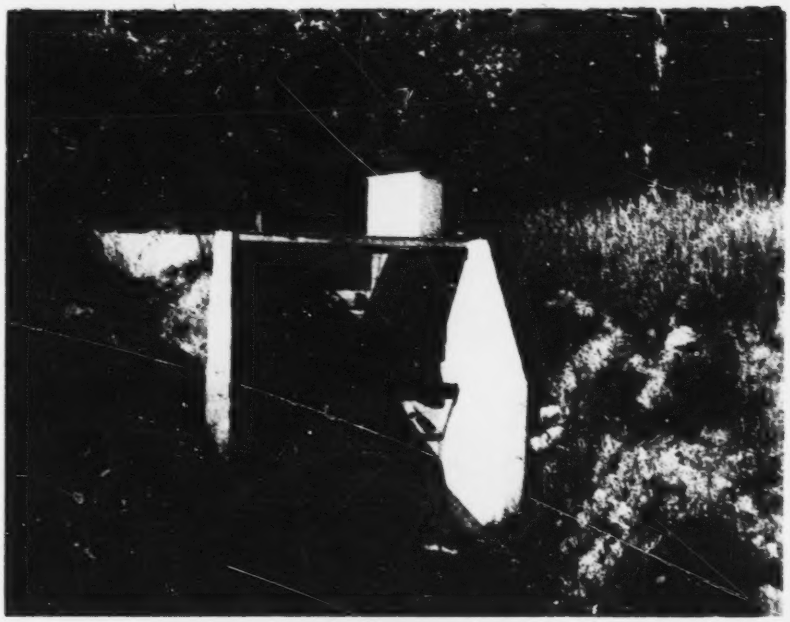

Figure 36. Flow Measuring Device (3 foot H-Flume) at M09 Small Watershed Site

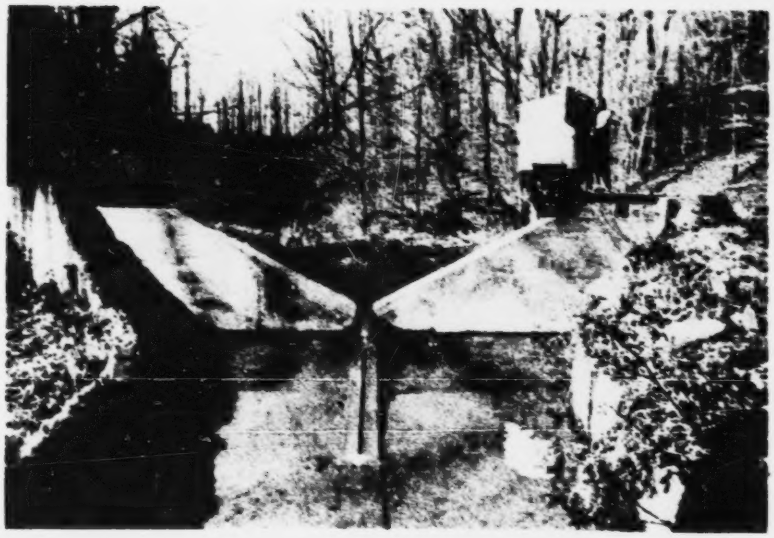

Figure 37. Broad-Crested V-Notch Weir at A06 Site

Table 23. Hydrologic and Weather Parameters Recorded, Frequency of Measurement, and Record Periods

Hydrologic Component	Watershed Site									
	C06		M09		J11		J08		A06	
	Freq.[1]	Dates[2]	Freq.	Dates	Freq.	Dates	Freq.	Dates	Freq.	Dates
Runoff--------------- (Outlet)[3]	C	1/1/76-11/3/76	C	6/8/76-1/19/77	C	5/1/77-12/31/77	N	----	C	7/3/75-12/31/77
Runoff--------------- (Small Watershed)	N	----	C	6/1/76-2/8/77	C	5/24/77-12/31/77	N	----	C	9/5/75-12/31/77
Precipitation-------	C	12/6/75-11/3/76	C	5/1/76-1/19/77	C	5/1/77-12/31/77	N	----	C	7/10/75-12/31/77
Soil Moisture-------	P	12/31/75-11/3/76	P	6/16/76-1/19/77	P	6/3/77-12/31/77	N	----	P	12/29/76-12/31/77
Spring Discharge----	C	2/24/76-1/3/77	C	4/29/76-6/7/77	N	----	N	----	C	7/30/75-12/31/77
Solar Radiation-----	N	----	N	----	N	----	N	----	C	6/1/75-12/31/77
Wind Speed----------	C	4/17/76-11/3/76	C	6/8/76-1/19/77	N	----	N	----	C	7/1/75-12/31/77
Air Temperature-----	C	12/7/75-11/3/76	C	5/6/76-1/19/77	C	5/1/77-12/31/77	N	----	C	7/1/75-12/31/77
Relative Humidity---	C	12/7/75-11/3/76	C	5/6/76-1/19/77	C	5/1/77-12/31/77	N	----	C	7/1/75-12/31/77
Snow and Frozen Soil	P	12/23/75-11/3/76	P	11/30/76-1/19/77	P	11/28/77-12/31/77	N	----	P	12/29/76-12/31/77

[1] C - Continually; P - Periodic; N - Not Collected ----- [2] Inclusive dates ---- [3] Outlet runoff dates determine the premining data periods for C06 and M09 sites. The J11 and A06 sites have not been mined as of 12/31/77.

2. Precipitation

Summer precipitation at the study watersheds comes predominately from convectional storms. These storms are of high intensity, but of short duration over small areas. Winter precipitation results from cyclonic storms and frontal systems and is of lower intensity, but of longer duration and over larger areas. On the average, monthly precipitation is greatest from March through July.

The long-term average monthly precipitation record for a National Weather Service precipitation gage located near each watershed site was obtained for comparison with the observed monthly precipitation of the short-term record. The monthly recorded precipitation for the unshielded gage at the study sites was utilized along with the monthly totals of computed precipitation where available. Months without complete precipitation data, as at the beginning and end of the premining periods, were not used in the following tables that compare monthly data.

a. Watershed C06

The premining precipitation record for the C06 site extended from December 6, 1975 through November 3, 1976 (about 11 months). For comparison of precipitation data, the time period considered was from December 1, 1975 through October 31, 1976. Plots of monthly precipitation for gage 103 are shown in Figure 38. This gage, part of a network at the North Appalachian Experimental Watershed, is located approximately 14 miles northwest of the C06 site. Gage C06 was located in an exposed area near the toe of a southeasterly-facing slope, and about 200 feet west of the C06 outlet weir (Figure 2).

Monthly data and percentage difference from the long-term averages are listed in Table 24. The difference between the average and recorded precipitation for the period at gage 103 was less than 1 percent. The time distribution, however, showed great variations (Figure 38). April and May were extremely dry, being 40 to 46 percent below average, respectively, while August was high by 30 percent.

Plots of monthly unshielded and computed precipitation for the C06 site are shown in Figure 38. A precipitation summary for the site is given in Table 25. Monthly precipitation for the unshielded gage at C06 matches gage 103 values rather well (Table 24), considering that the gages are about 14 miles apart. The greatest deviations occur in the summer as a result of localized thunderstorms. The monthly computed values are only slightly higher than the observed unshielded gage values except during the winter months when the wind effect on snowfall causes an 11 percent deficit in catch by the unshielded gage for the period (Table 25). Snowfall accounted for 5 percent of the computed precipitation.

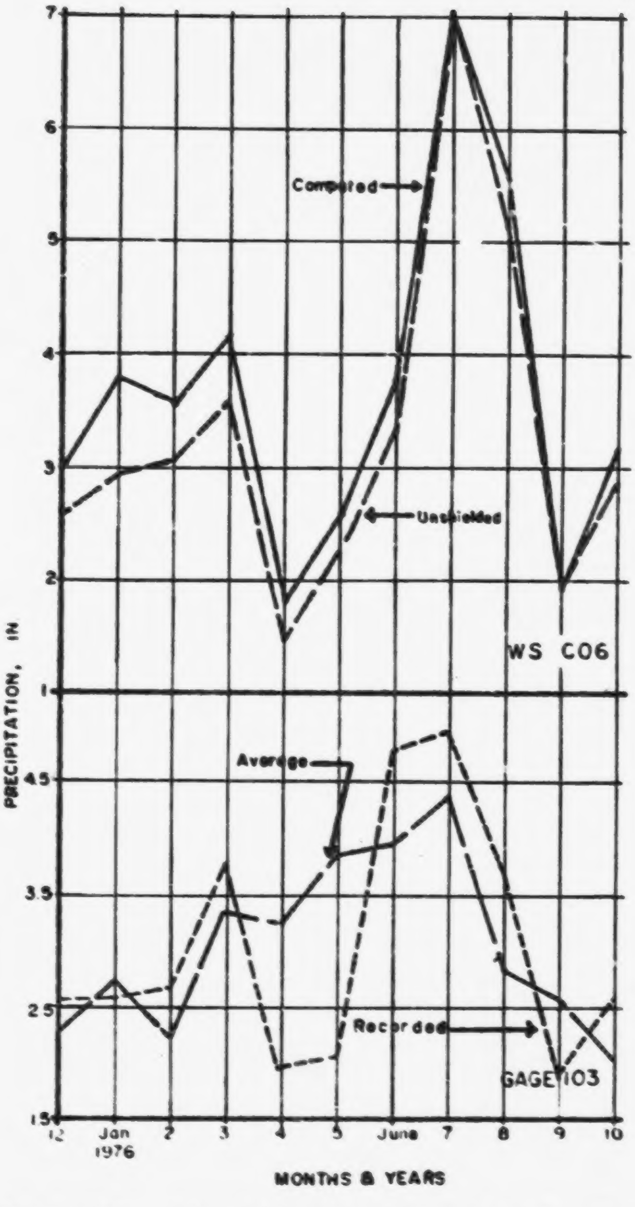

Figure 38. Time Distributions of Monthly Premining Precipitation Associated with Watershed C06

Table 24. Average, Observed, and Computed Premining Precipitation Associated with Watershed C06

Gage	Year and Month											Totals or Avg.
	1975	1976										
	12	1	2	3	4	5	6	7	8	9	10	
Gage 103 30-yr. Avg. (In.)	2.24	2.71	2.21	3.33	3.23	3.81	3.93	4.37	2.82	2.58	2.03	33.26
Gage 103 Recorded (In.)	2.55	2.58	2.68	3.76	1.95	2.06	4.79	4.93	3.68	1.92	2.57	33.47
Gage 103 % Diff.	+14	-5	+21	+13	-40	-46	+22	+13	+30	-26	+27	<1
C06 Unshielded (In.)	2.58	2.91	3.04	3.59	1.46	2.26	3.36	7.00	5.16	1.94	2.82	36.12
C06 Computed (In.)	2.98	3.79	3.59	4.29	1.82	2.55	3.75	7.05	5.43	1.94	3.18	40.37

Table 25. Premining Precipitation Summary for Watershed C06

Period of Pre-Mining Record	Dec. 6, 1975 through Nov. 3, 1976
Total Number of Storms[1]	156
Unshielded Precipitation (In.)	Total: 36.12, Snow 1.32 (Snow, 4% of total)
Computed Precipitation (In.)	Total: 40.37, Snow 1.90 (Snow, 5% of total)
Ratio: $\frac{\text{Unsh. Prec.}}{\text{Comp. Prec.}}$	89%
Largest Storm[2] (Unshielded Values)	
Date	July 8, 1976
Total (In.)	1.65
Length (Hrs.)	12.03
Approx. Assoc. Frequency[3]	1.60 Inches in 2 hours for an approximate 5-year event.
Peak Intensity	5.16 In./Hr. for 5 minutes totaling 0.43 Inches.

---

[1] Storms are separated by periods of no precipitation for 1 hour.
[2] This storm caused the highest peak flow for the premining period.
[3] The estimated 2-hour, 5-year event (Hershfield, 1961) is 1.70 inches.

The most extreme event during the premining phase occurred on July 8, 1976 and produced 1.65 inches of rainfall. The peak intensity of 5.16 in./hr. lasted 5 minutes, totaling 0.43 inches of water. The highest 2-hour intensity of 1.60 inches was approximately a 5-year event.

b. Watershed M09

The premining precipitation record for the M09 site extended from May 1, 1976 through January 19, 1977 (about 9 months). For comparison of precipitation data, the time period was from May 1, 1976 through January 31, 1977. Plots of the average and recorded precipitation for this period for the National Weather Service gage at Philo 3SW are shown in Figure 39. The gage is located about 10.5 miles west of the M09 site. Gage M09 is located on an exposed southwesterly-facing slope about 400 feet from the outlet weir (Figure 3).

Monthly data and percentage differences from the long-term averages are listed in Table 26. The difference between the average and recorded precipitation for this period at Philo 3SW was 3 percent. In comparing the monthly values, it is seen that July was particularly wet and the late fall and early winter excessively dry.

Plots of monthly unshielded and computed precipitation for the M09 site are shown in Figure 39. A precipitation summary for the site is given in Table 27. Monthly precipitation for the unshielded gage at M09 agrees rather well with that of Philo 3SW, considering that the gages are 10.5 miles apart. The unshielded and computed monthly precipitation agree well during the non-snowfall months. The computed amount exceeded that caught by the unshielded gage by 7 percent (Table 27). Snowfall accounted for 12 percent of the computed precipitation.

The most extreme event occurred on July 11, 1976 and produced 3.02 inches of rainfall--accounting for 54 percent of the monthly total. The peak intensity of 3.60 in./hr. lasted 3 minutes and contributed 0.18 inches of water. The highest 3-hour intensity of 2.73 inches was about a 25-year event.

c. Watershed J11

The record period for this report was from May 1, 1977 through December 31, 1977. Plots of monthly precipitation for the National Weather Service gage at Cadiz, located about 9 miles northwest of the J11 site, are shown in Figure 40. Gage J11 is located about 1,300 feet east of the J11 outlet weir and just out of the watershed boundary at an exposed site (Figure 4).

Monthly data and percentage difference from the long-term averages are listed in Table 28. The difference between the average and recorded precipitation for the period at Cadiz was 19 percent more than the long-term average. Following a dry May, more than average precipitation fell during the period June through September.

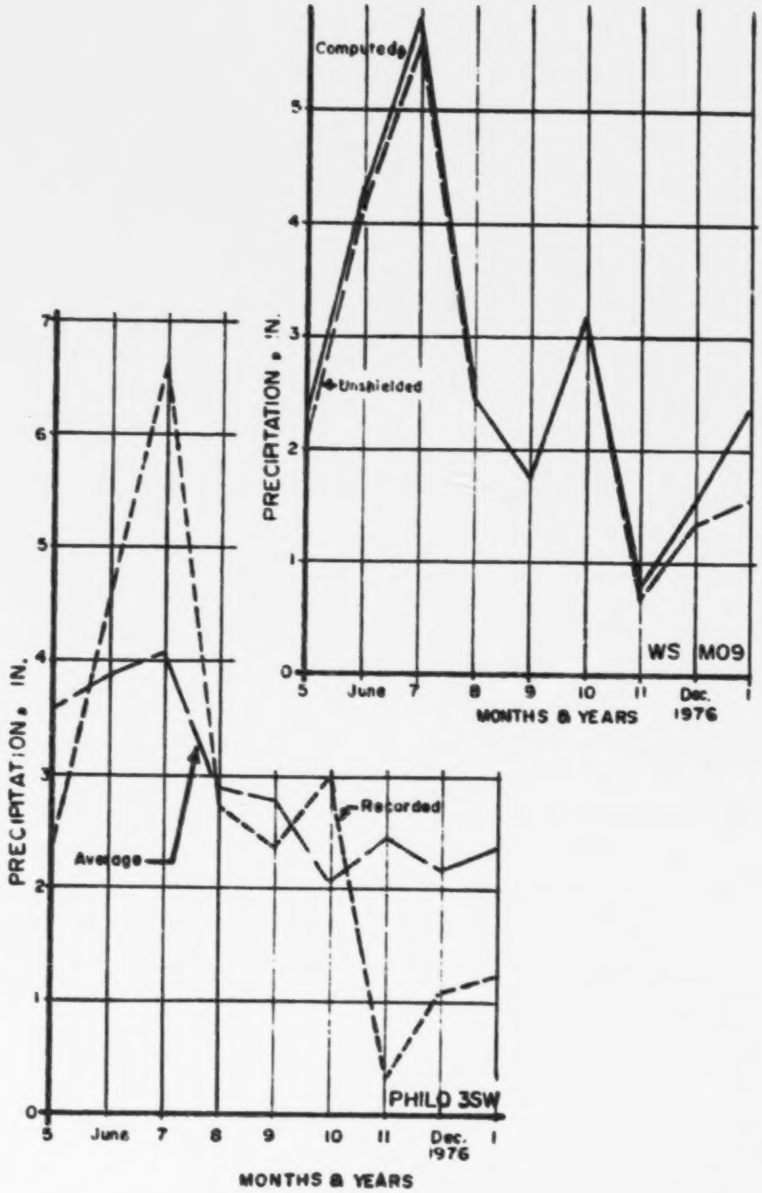

Figure 39. Time Distributions of Monthly Premining Precipitation Associated with Watershed M09

Table 26. Average, Observed, and Computed Premining Monthly Precipitation Associated with Watershed M09.

Gage	Year and Month									Total or Avg.
	1976								1977	
	5	6	7	8	9	10	11	12	1	
30-yr.avg. Philo 3SW (In.)	3.57	3.84	4.05	2.88	2.77	2.05	2.42	2.17	2.36	26.11
Philo 3SW rec. (In.)	2.31	4.54	6.58	2.72	2.38	2.98	.30	1.06	1.23	24.10
Philo 3SW % Difference	-35	+18	+62	-6	-14	+45	-88	-51	-48	-8
M09 Unshielded (In.)	2.06	4.17	5.58	2.48	1.84	3.12	.66	1.31	1.25	22.47
M09 Computed (In.)	2.31	4.26	5.78	2.48	1.85	3.20	.79	1.54	1.83	24.04

Table 27. Premining Precipitation Summary for Watershed M09

Period of Pre-Mining Record	May 1, 1976 through Jan. 19, 1977
Total Number of Storms[1]	106
Unshielded Precipitation (In.)	Total: 22.47, Snow 2.13 (Snow, 9% of total)
Computed Precipitation (In.)	Total: 24.04, Snow 2.94 (Snow, 12% of total)
Ratio: $\frac{\text{Unsh. Prec.}}{\text{Comp. Prec.}}$	93%
Largest Storm[2] (Unshielded Values)	
Date	July 11, 1976
Total (In.)	3.02
Length (Hrs.)	3.43
Approx. Assoc.	2.73 Inches in 3 hours for an approximate 25-year event[3]
Peak Intensity	3.60 In./Hr. for 3 minutes totaling 0.18 Inches

---

[1] Storms are separated by periods of no precipitation for 1 hour.
[2] This storm caused the highest peak flow for the premining period.
[3] The estimated 3-hour, 25-year event (Hershfield, 1961) is 2.70 inches.

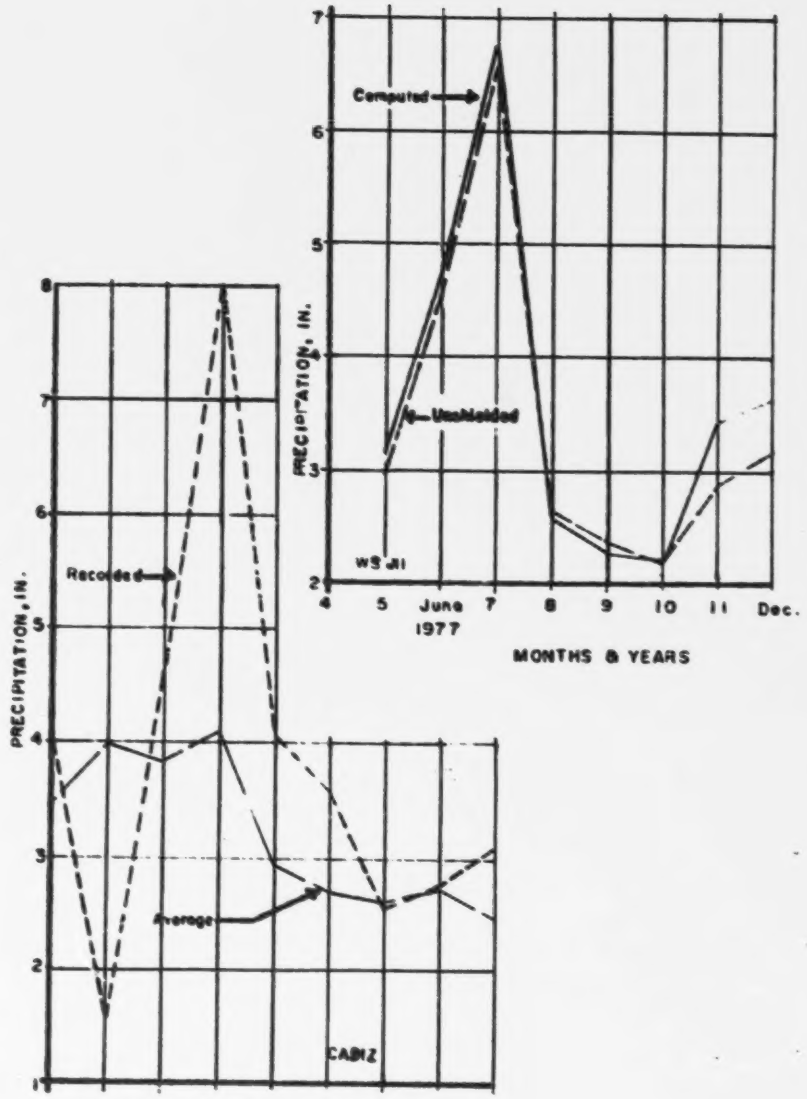

Figure 40. Time Distributions of Monthly Premining Precipitation Associated with Watershed J11

Table 28. Average, Observed, and Computed Monthly Precipitation Associated with Watershed J11.

Gage	Year and Month 1977								Totals or Avg.
	5	6	7	8	9	10	11	12	
Cadiz Average 30yr. (In.)	3.97	3.81	4.09	2.95	2.70	2.61	2.71	2.46	25.30
Cadiz Recorded (In.)	1.50	4.59	8.05	4.06	3.55	2.55	2.74	3.09	30.13
% Difference	-62	+20	+97	+38	+31	-2	+1	+26	+19
J11 Unshielded (In.)	2.92	4.53	6.52	2.61	2.38	2.17	2.86	3.15	27.14
J11 Computed (In.)	3.12	4.68	6.73	2.58	2.28	2.21	3.42	3.62	28.64

Plots of monthly unshielded and computed precipitation for the J11 site are shown in Figure 40. A precipitation summary for the site is given in Table 29. The unshielded gage caught considerably more precipitation in May but less in the summer than the Cadiz gage. The reason for the difference is probably due to localized thunderstorms. The computed total was 5 percent higher than the unshielded total (Table 29) and would have been greater had the entire winter season been included in the record. Snowfall, for this situation, amounted to 5 percent of the computed precipitation.

The most extreme event during the period occurred on July 21, 1977 and produced 1.93 inches of water. The peak intensity of 7.50 in./hr. lasted for 2 minutes, totaling 0.25 inches of water. The highest 3-hour rainfall of 1.66 inches was about a 2-year event.

d. Watershed A06

The record period considered for the control watershed was from July 1, 1975 through December 31, 1977. Figure 41 shows monthly precipitation for gage 103 which is located about 1,400 feet from the center of Watershed A06. The actual record began July 10, 1975, and thus the July, 1975 value in Figure 41 is too low. The monthly data and percentage differences from the long-term averages are listed in Table 30. For long-term precipitation comparisons, gage 103 was used throughout the year, but a composite record was developed (Table 30) for project use. July, 1975 was not considered in Table 30. The recorded precipitation for gage 103 for the whole period was only 3 percent above average. A comparison of the monthly data revealed that October 1975 through October 1976 closely followed the long-term average. The remainder of the record showed a drier than average winter for the 1976-77 season, and a wetter than average summer and winter in 1977.

The composite precipitation (Table 30), containing computed values for snowfall over a portion of the record, is plotted in Figure 41. Precipitation data for the site is summarized in Table 31. Inclusion of computed value of snowfall for 2 of the 3 winters increased the total precipitation amount by 5 percent. Snowfall accounted for 4 percent of the total composite precipitation.

The most extreme event during the period occurred on July 11, 1976 giving 1.75 inches of rainfall. The peak of 6.30 in./hr. lasted 2 minutes, totaling 0.21 inches of water. The highest 1-hour rainfall of 1.61 inches was about a 5-year event.

Table 29. Precipitation Summary for Watershed J11

Period of Pre-Mining Record	May 1, 1977 through Dec. 31, 1977
Total Number of Storms[1]	131
Unshielded Precipitation (In.)	Total: 27.14, Snow 1.06 (Snow, 4% of total)
Computed Precipitation (In.)	Total: 28.64, Snow 1.42 (Snow, 5% of total)
Ratio: $\frac{\text{Unsh. Prec.}}{\text{Comp. Prec.}}$	95%
Largest Storm[2] (Unshielded Values)	
Date	July 21, 1977
Total (In.)	1.93
Length (Hrs.)	5.32
Approx. Assoc. Frequency	1.66 Inches in 3 hours for a 2-year event.[3]
Peak Intensity	7.50 In./Hr. for 2 minutes totaling 0.25 Inches

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[1] Storms are separated by periods of no precipitation for 1 hour.
[2] This storm caused the highest peak flow for the record period.
[3] The estimated 3-hour, 2-year event (Hershfield, 1961) is 1.60 inches.

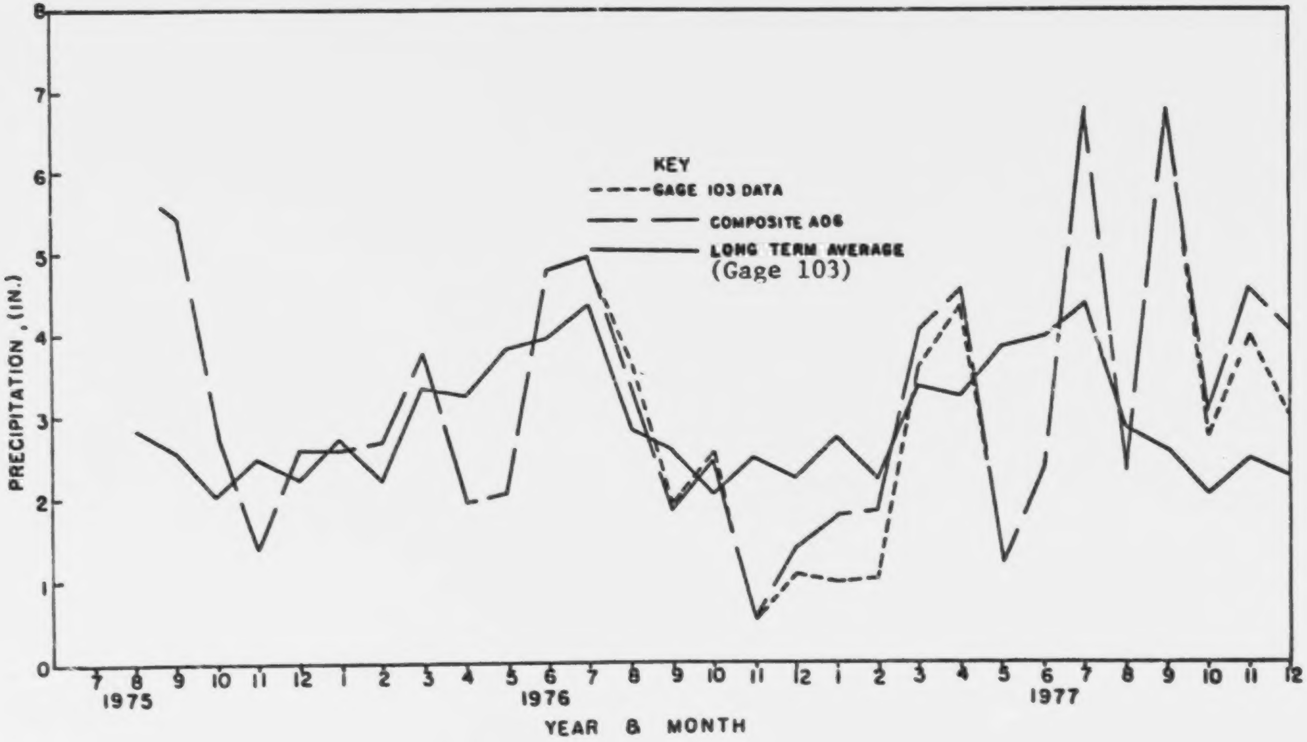

Figure 41. Time Distributions of Monthly Precipitation Associated with Watershed A06

Table 30. Average, Observed, and Computed Precipitation Associated with Watershed A06

Gage	Year and Month					Total or Avg.	Year and Month				
	1975						1976				
	8	9	10	11	12	(1975)	1	2	3	4	5
Gage 103 30-yr. avg. (In.)	2.82	2.58	2.03	2.49	2.24	12.16	2.71	2.21	3.33	3.23	3.81
Gage 103 Recorded (In.)	5.84	5.43	2.76	1.36	2.55	17.94	2.58	2.68	3.76	1.95	2.06
Gage 103 % Difference	+107	+110	+36	-45	+14	+48	-5	+21	+13	-40	-46

	Year and Month							Total or Avg.	Year and Month			
	1976								1977			
	6	7	8	9	10	11	12	(1976)	1	2	3	4
Gage 103 30-yr. Avg. (In.)	3.93	4.37	2.82	2.58	2.03	2.49	2.24	35.75	2.71	2.21	3.33	3.23
Gage 103 Recorded (In.)	4.79	4.93	3.68	1.92	2.57	.49	1.07	32.48	.98	1.04	3.57	4.33
Gage 103 % Difference	+22	+13	+30	-26	+27	-80	-52	-9	-64	-53	+7	+34
A06 Composite[1] (In.)	4.79	4.93	3.68	1.84	2.46	.54	1.40	32.67	1.80	1.84	4.05	4.54

Table 30. (Cont'd) Average, Observed, and Computed Precipitation Associated with Watershed A06.

Gage	Year and Month								Total or Avg. (1977)	Totals or Avg. for Record
	1977									
	5	6	7	8	9	10	11	12		
Gage 103 30-yr. avg. (In.)	3.81	3.93	4.37	2.82	2.58	2.03	2.49	2.24	35.75	83.66
Gage 103 Recorded (In.)	1.17	2.34	6.76	2.29	6.76	2.74	3.95	2.93	38.86	89.28
Gage 103 % Difference	-69	-40	+55	-19	+162	+35	+59	+31	+9	+7
A06 Composite[1]	1.17	2.34	6.76	2.29	6.78	3.05	4.54	4.02	43.18	95.32

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[1] A06 composite precipitation for the premining period is composed of gage 103 data from August 1975 through August 1976, gage LY3 from September 1976 through April 1977, and gage 103 from May 1977 through December 1977.

Table 31. Precipitation Summary for Watershed A06

Period of Premining Record	July 10, 1975 through Dec. 31, 1977
Total Number of Storms[1]	416
Composite Precipitation (In.)	Total: 95.32, Snow 3.78 (Snow, 4% of total)
Largest Storm[2] (Unshielded Values)	
Date	July 11, 1976
Total (In.)	1.75
Length (Hrs.)	1.60
Approx. Assoc. Frequency	1.61 Inches in 1 hour for a 5-year event.[3]
Peak Intensity	6.30 In./Hr. for 2 minutes totaling 0.21 Inches

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[1] Storms are separated by periods of no precipitation for 1 hour.
[2] This storm caused the highest peak flow for the period.
[3] The estimated 1-hour, 5-year event (Hershfield, 1961) is 1.58 inches.

3. Air Temperature

The temperature data were tabulated every 3 hours, along with the absolute maximum and minimum values. The monthly averages for the period of record for all watersheds were tabulated in Table 32 with those of the long-term averages at A06. The data show that there was not much difference between temperatures at each of the study sites for overlapping records and also when compared to the A06 record. Therefore, the A06 39-year average was used in comparing the temperature data associated with each study site for the respective record periods.

The average C06 temperature record was close to the long term average at A06 (51°F for each). Deviations in the time distribution occurred in the late winter, when it was unusually warm, and in the fall, when it was moderately cool.

The average M09 temperature for the period of record was 48.9°F, about 5 degrees below the average long-term record at A06 (54.0°F). The recorded temperatures were almost always below the average and decreased to about 13 degrees below average by the end of the observation period (January, 1977).

The J11 record showed the average period of record temperature, 56.9°F, was less than one degree below the average at A06 (57.5°F). The temperature pattern resembled that of the average at A06.

The 39-year average temperature for the A06 record period was 51.2°F, 0.1°F greater than the recorded average of 51.1°F. The monthly temperature departures were calculated and entered in Table 32. The record shows a warm fall (1975), a warm spring (1976), an average summer (1976), an extremely cold fall and winter (1976), and an average year for 1977.

4. Relative Humidity

Relative humidity data are important for the determination of evapotranspiration from the watershed. The relative humidity data were tabulated every 3 hours and monthly averages obtained. The averages for the period of record for all watersheds were tabulated in Table 33, with those of the long-term averages at A06, as was done for the temperature data. Humidities at the C06, M09, and J11 sites were higher than at the A06 site most of the time. It is possible that unknown site specific factors were responsible for these differences. Therefore, the long-term relative humidity data at A06 cannot be compared with those of the other sites. However, the short-term A06 record can be compared with its long-term record.

The data in Table 33 show that the A06 monthly relative humidity for the period record was less than the long-term average most of the

Table 32. Summary of Average Monthly Temperature (^{o}F) for all Study Sites.

Site	Year and Month														
	1975						1976								
	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9
C06	-	-	-	-	-	32.2	24.7	38.9	45.9	49.3	56.7	68.7	68.4	67.3	61.5
M09	-	-	-	-	-	-	-	-	-	-	57.2E	68.4	69.4	66.6	60.9
J11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A06, Rec.	72.3	73.2	59.3	54.6	46.3	33.5	22.4	37.0	45.7	50.9	56.8	69.5	69.7	68.0	61.3
A06, Avg.[1]	72.2	71.0	64.1	53.4	40.5	30.4	26.5	28.8	37.6	49.2	59.6	68.5	72.2	71.0	64.1
A06, Depart.	+0.1	+2.2	-4.8	+1.2	+5.8	+3.1	-4.1	+8.2	+8.1	+1.7	-2.8	+1.0	-2.5	-3.0	-2.8

	Year and Month														
	1976			1977											
	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
C06	47.6	37.9E	-	-	-	-	-	-	-	-	-	-	-	-	-
M09	46.6	33.3	24.4	13.0E	-	-	-	-	-	-	-	-	-	-	-
J11	-	-	-	-	-	-	-	63.8	64.6	72.4	69.2	65.3	49.3	43.0	27.9
A06, Rec.	47.8	33.7	24.2	12.2	26.7	45.6	53.9	66.8	66.5	74.4	71.1	66.7	51.2	44.1	28.6
A06, Avg.[1]	53.4	40.5	30.4	26.5	28.8	37.6	49.2	59.6	68.5	72.2	71.0	64.1	53.4	40.5	30.4
A06, Depart.	-5.6	-6.8	-6.2	-14.3	-2.1	+8.0	+4.7	+7.2	-2.0	+2.2	+.1	+2.6	-2.2	+3.6	-1.8

[E] Estimations for portion of missing record.

[1] 39-year average

Table 33. Summary of Average Monthly Relative Humidity Data (%)

Site	Year and Month														
	1975						1976								
	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9
C06	-	-	-	-	-	74.6	75.4	68.5	69.1	69.6	69.4	71.1	71.0	74.3	75.1
M09	-	-	-	-	-	-	-	-	-	-	67.5	76.9	73.8	78.4	73.5
J11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
A06, Rec.	71.2	76.0	79.7	72.3	71.3	73.2	74.2	63.6	61.1	57.7	62.2	66.0	69.6	70.3	68.5
A06[1]	70.9	72.3	74.1	72.5	75.4	79.5	70.9	71.8	68.4	69.5	67.7	70.9	70.9	72.3	74.1
A06, % Diff.	+.4	+5	+8	-.3	-5	-8	+5	-11	-11	-17	-8	-7	-2	-3	-8

	Year and Month														
	1976			1977											
	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
C06	74.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
M09	73.5	72.1	75.7	72.8	-	-	-	-	-	-	-	-	-	-	-
J11	-	-	-	-	-	-	-	63.4	72.0	74.2	76.1	75.5	74.0	81.9	82.8
A06, Rec.	66.4	69.9	72.7	71.2	63.4	53.2	67.8	67.6	67.5	70.7	75.7	77.6	71.3	75.5	75.3
A06[1]	72.5	75.4	79.5	70.9	71.8	68.4	69.5	67.7	70.9	70.9	72.3	74.1	72.5	75.4	79.5
A06, % Diff.	-8	-7	-9	+.4	-12	-22	-2	-.1	-5	-.3	+5	+5	-2	+.1	-5

[1] 24-yr. average

time, the maximum percent difference occurring in March 1977 (-22%). The summers of 1975 and 1977 show an above average relative humidity, the maximum being 8 percent.

5. Solar Radiation

Integrated hourly values of incident solar radiation were recorded at J11 and A06. These data were summed to give a total daily value of solar radiation in langleys. The only useful data for the premining period were those collected at A06.

The monthly A06 data were compared with the long-term monthly averages at Wooster, Ohio, located 40 miles to the north of the A06 site. The records for both and their percent differences are given in Table 34. Recorded A06 data were almost always lower than the long-term Wooster average. The differences were substantial, ranging from -.6 to -50 percent. The apparent discrepancy in the records will be investigated.

Table 34. Average Monthly Solar Radiation Data Associated With Watershed A06.

Site	Year and Month															
	1975							1976								
	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9
Wooster Avg. (Langleys)	508	503	444	354	272	159	133	174	237	286	368	462	508	503	444	354
A06 Recorded (Langleys)	532	578	414	292	238	158	111	119	183	239	404	444	432	411	368	298
A06 Difference	+5	+15	-7	-18	-12	>-1	-17	-32	-23	-16	+9	-4	-15	-18	-17	-16

	Year and Month														
	1976			1977											
	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Wooster Avg. (Langleys)	272	159	133	174	237	286	368	462	508	503	444	354	272	159	133
A06 Recorded (Langleys)	188	158	115	147	187	252	308	446	387	404	323	259	186	80	69
A06 % Difference	-31	>-1	-14	-16	-21	-12	-16	-3	-24	-20	-27	-27	-32	-50	-48

6. Wind

A summary of the range of average daily wind speeds for the C06, M09, and A06 sites is given in Table 35. Data for the J11 site were not collected for this part of its premining phase. Generally, wind speeds were much greater at A06 than at the other sites. This is probably due to the greater exposure of the wind instrument near the A06 site.

Table 35. Summary of the Range of 2-Meter Average Daily Wind Speeds

Site	Range of Average Daily Wind Speed (mph)
C06	0.2 to 5.8
M09	0.7 to 5.0
A06	1.2 to 9.5

7. Snow and Frozen Ground

The snow data indicate that there was snow on the ground (100% cover) for much of the 1976-77 fall and winter seasons and all of the 1977-78 winter season for the M09, J11, and A06 sites. Intermittent snow cover existed at the C06 site during the 1975-76 winter season, prior to mining.

Extreme snow and frozen ground data are summarized in Table 36 for all the study sites. The deepest snow measured was 11.5 inches at the M09 site. The largest water content in the snow pack was also at M09: 1.82 inches of water in 10.5 inches of snow. The deepest depth of frozen ground was 8 inches at the C06 site.

8. Soil Moisture

In presenting the average soil moisture data for each watershed, no attempt was made to assign weights to the individual soil moisture tubes. Because the tubes were distributed over the entire watershed, an unweighted average was used. The enveloping curves of soil moisture, derived by plotting the maximum values for each depth, are presented for each site, as are time traces of average watershed soil moisture.

Table 36. Summary of Extreme Snow and Frozen Soil Data

Site	Max. Snow Depth (In.)	Assoc. H_2O Content (In.)	Location	Date	Max. H_2O Content (In.)	Assoc. Snow Depth (In.)	Location	Date	Max. Frost Depth (In.)	Location	Date
C06	6.5	-	#16 tube	1/22/76	0.35	1.0	Instrument Plot	1/15/76	8.0	Open Area	2/2/76 & 2/9/76
M09	11.5	-	#14 tube	1/18/77	1.82	10.5	#10 tube	1/18/77	2.0	Several Tubes	1/4/77
J11	3.0	.61	Instrument Plot	12/9/77	0.61	3.0	Instrument Plot	12/9/77	3.0	Several Tubes	12/30/77
A06	2.4	-	Instrument Plot	12/29/76	-	-	-	-	2.0	Several Tubes	12/29/76 & 12/28/77

The record periods for each watershed did not overlap in all cases; therefore, the data were collected during different weather patterns. Also, a completion of a yearly cycle of watershed soil moisture was precluded by the mining activity at C06 and M09 and by the arbitrary cut-off date of December 31, 1977 for J11. Data are not available for the M09 and J11 sites for the winter and spring seasons, but all seasons are fairly well represented for the C06 and A06 sites. Soil moisture data were not collected at J08. Data were collected once every one or two weeks at all sites.

The enveloping curves for soil moisture depth distributions throughout the time period for each watershed are shown in Figure 42. All graphs show the same basic shape - wide at the top and narrow at the bottom. This indicates that most hydrologic activity occurs in the top 9 inches. The 9-15 inch depth shows the next most active hydrologic zone. The 18-48 inch depths are least active. The wide variation of soil moisture in the 0-9 inch zone reflects recharging due to precipitation and snowmelt, and discharging either to the atmosphere through evapotranspiration or to the ground-water zone through percolation (see Figure 26).

Table 37 summarizes the average watershed soil moisture data used to construct the enveloping curve in Figure 42. In terms of absolute percent by volume, soil moisture below the top 9 inches increased in Watersheds A06, C06, J11, and M09, in that order.

The table also shows that the ranges in soil moisture change, for the periods of record, decreased in the same order, A06, C06, J11, and M09. Coarser-textured residual soils can infiltrate and percolate water more readily than the finer textured soils. Superimposed on the soil characteristics was the effect of vegetative cover and root penetration. The watersheds were less forested in the same order, A06, C06, J11, and M09, and thus there was a decreasing opportunity for deeper withdrawal of water by roots by transpiration. Similar ranges in soil water contents due to vegetative cover were observed by Harrold and Dreibelbis (1967).

Time traces of average premined soil moisture for each watershed are presented in Figures 43-46. As noted, the surface to 9 inch zone was the most hydrogically active. If more frequent sampling was made, or if more sampling was made after storms and at the end of dry periods, the 0-9 inch graphs would have more and higher peaks and lower valleys. These figures also show that the fall and summer seasons had drier profiles than in the spring and winter, a consequence of the evapotranspiration exceeding precipitation during those seasons.

The extremes, dates, and ranges in total profile average watershed soil moisture for the periods of record are given in Table 38. The values for the range include the influence of the active 0-9 inch

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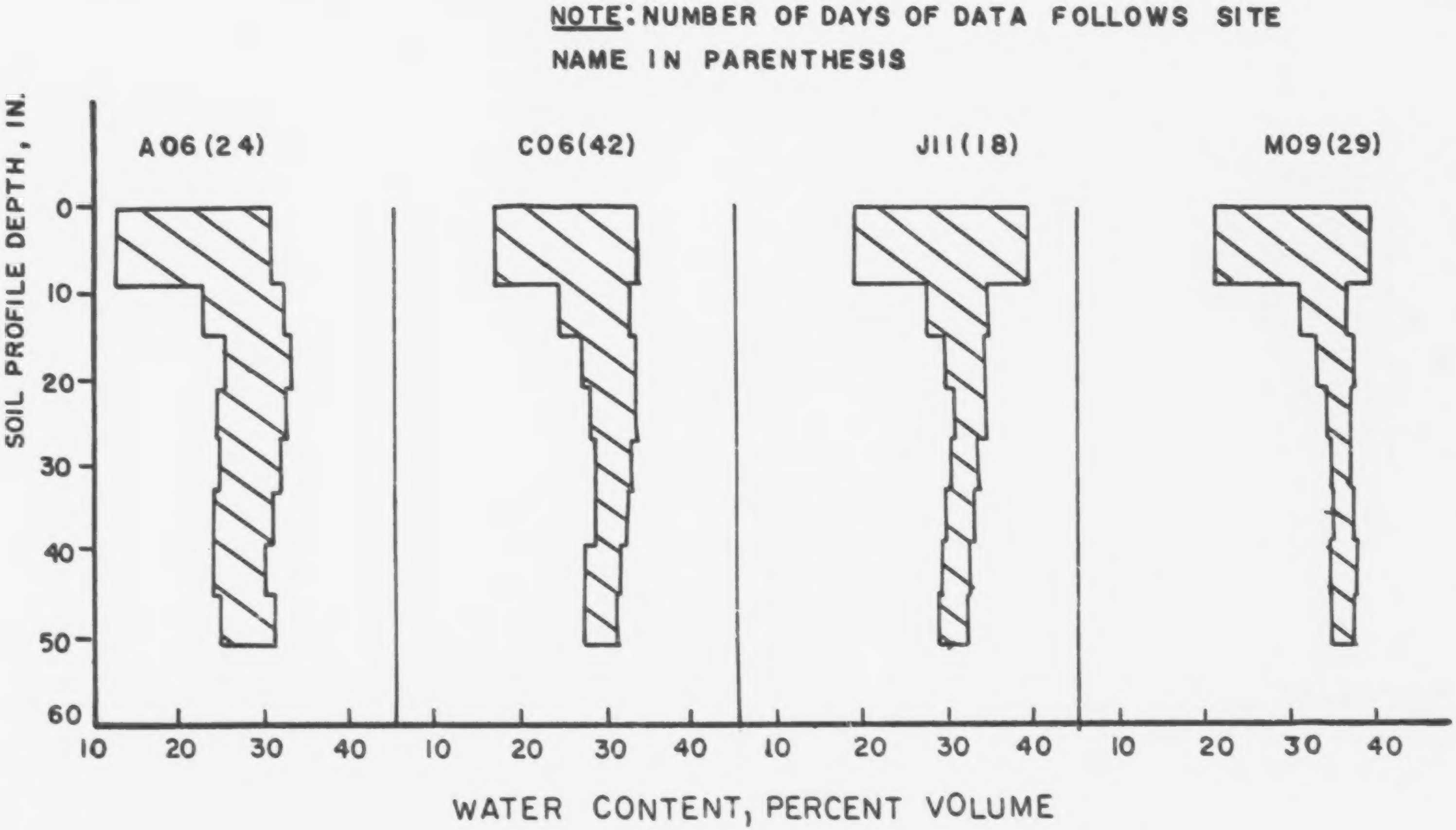

Figure 42. Enveloping Curves of Unmined Soil Moisture Distributions

Table 37. Average Watershed Soil Moisture Extremes (% water content by volume).

Site	Depth Range (In.)							
	0-9	9-15	15-21	21-27	27-33	33-39	39-40	45-51
A06								
MAX.	31.8	32.7	33.7	33.2	32.2	31.3	30.3	31.2
MIN.	13.3	23.7	26.0	25.3	24.8	24.2	24.0	25.0
DIFF.	18.5	9.0	7.7	7.9	7.4	7.1	6.3	6.2
C06								
MAX.	33.8	33.0	33.7	33.8	33.3	32.2	31.5	31.3
MIN.	17.2	25.5	27.5	28.3	28.7	28.7	27.7	27.7
DIFF.	16.6	7.5	6.2	5.5	4.6	3.5	3.8	3.6
J11								
MAX.	39.1	34.8	34.7	34.5	33.8	33.0	32.5	32.0
MIN.	19.1	27.8	29.8	30.7	30.2	29.7	29.3	29.0
DIFF.	20.0	7.0	4.9	3.8	3.6	3.3	3.2	3.0
M09								
MAX.	39.9	36.7	37.3	37.2	37.2	37.5	37.8	37.7
MIN.	21.4	31.5	33.8	34.7	34.8	35.2	34.7	34.7
DIFF.	18.5	5.2	3.5	2.5	2.4	2.3	3.2	3.0

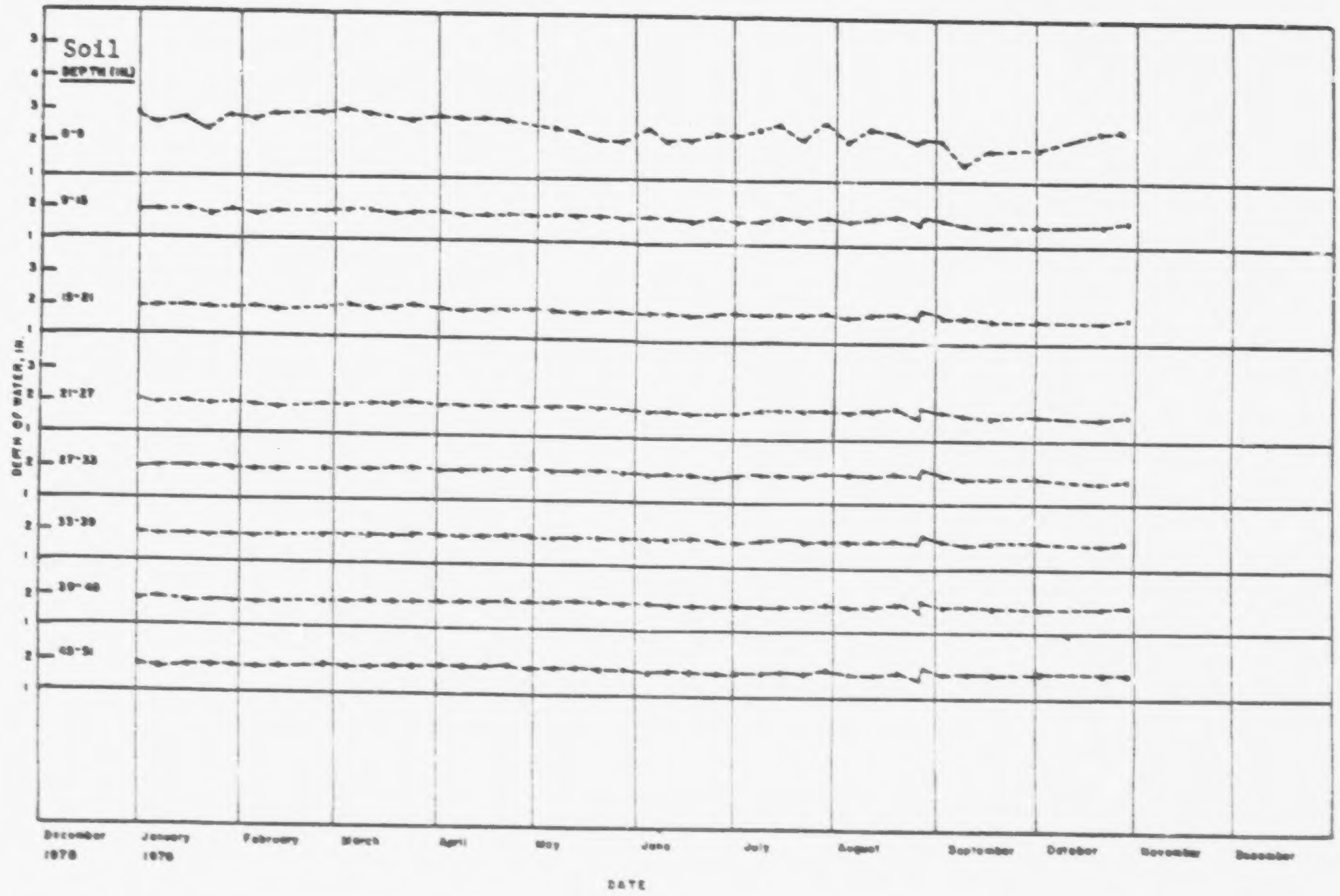

Figure 43. Time Distribution of Average Soil Moisture at Different Depths for Unmined Watershed C06

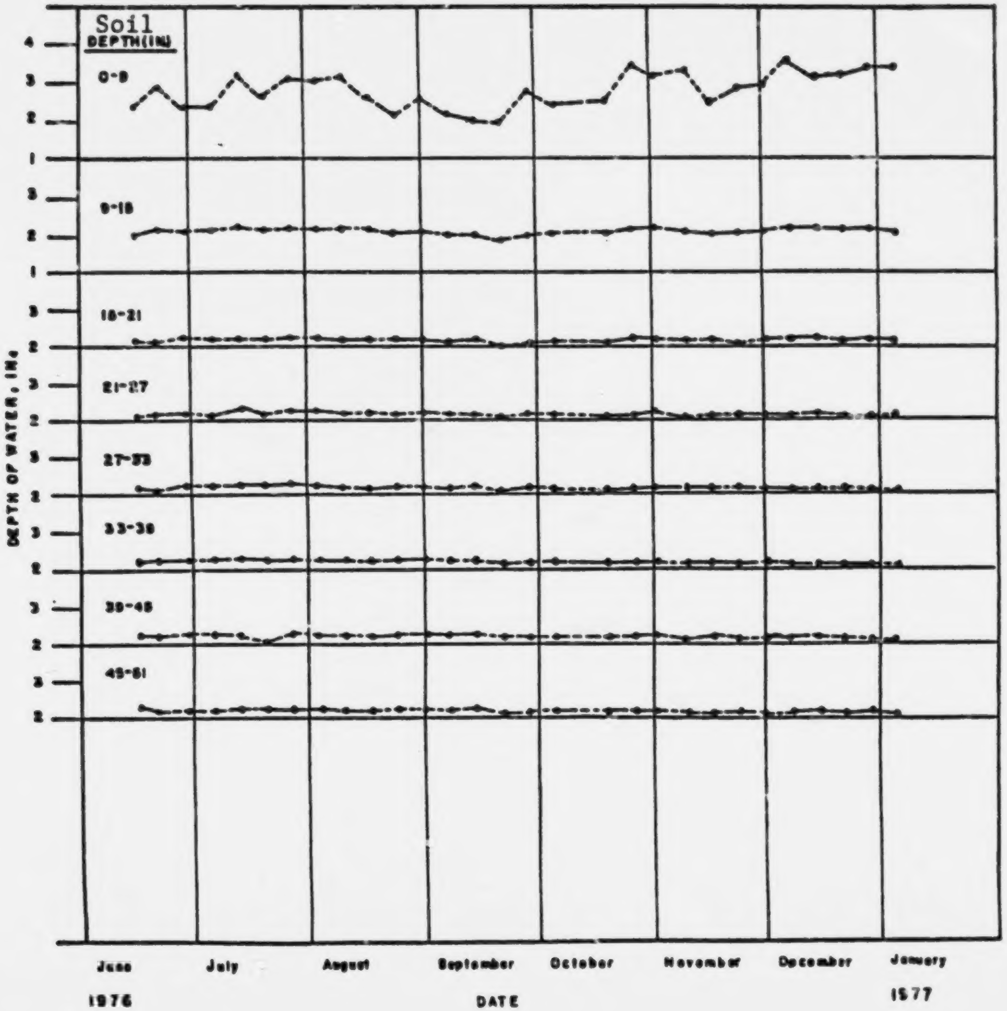

Figure 44. Time Distribution of Average Soil Moisture at Different Depths for Unmined Watershed M09

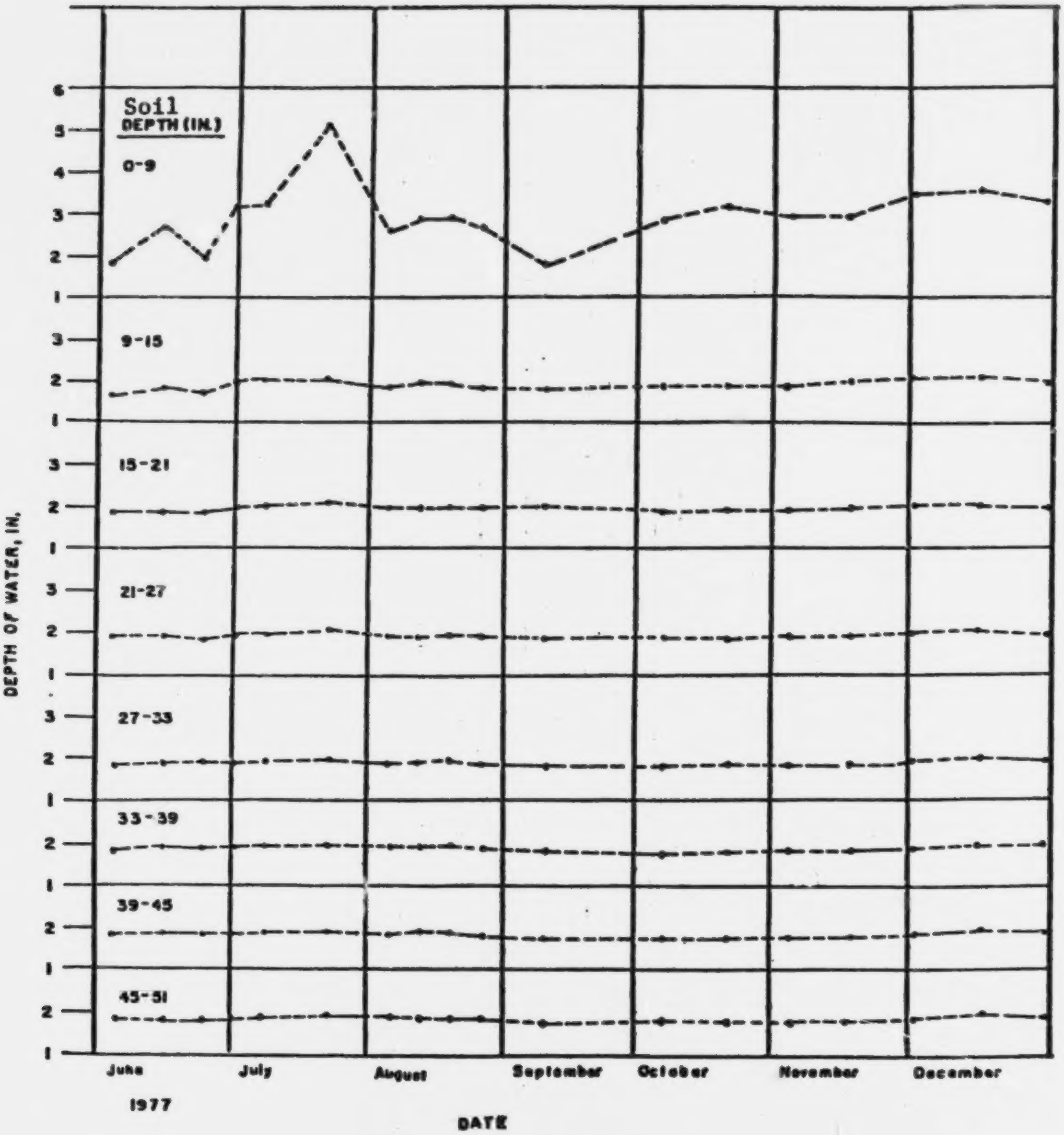

Figure 45. Time Distribution of Average Soil Moisture at Different Depths for Unmined Watershed J11

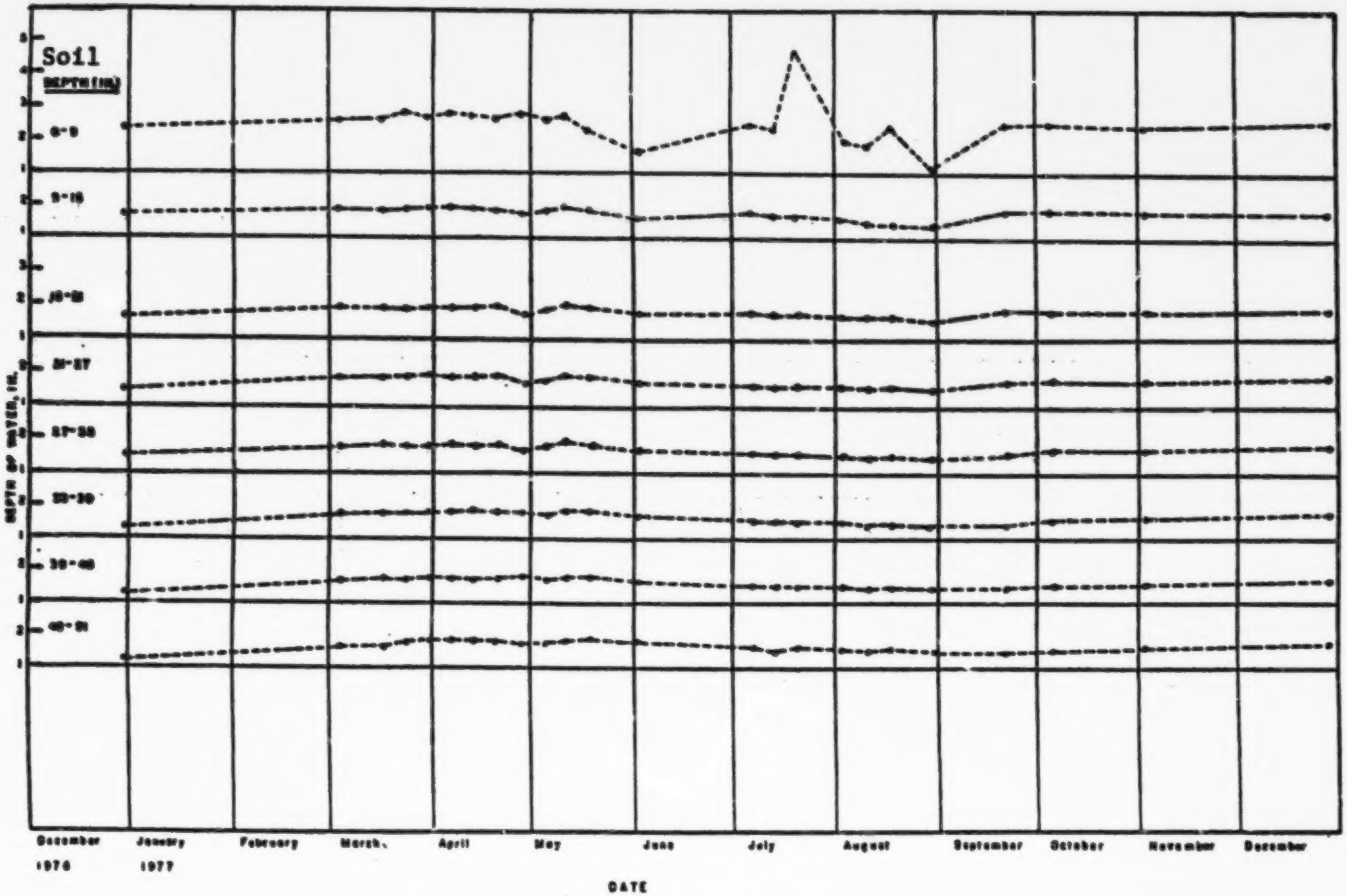

Figure 45. Time Distribution of Average Soil Moisture at Different Depths for Unmined Watershed A06

horizon, the values for which may have been taken at any time, including immediately after a storm, causing large variations in total profile moisture.

Because differences in soil moisture storage were an indication of the infiltration and percolation capabilities of the watersheds, they had differing runoff potential for any given event. It appears from the data that watershed runoff potential increased in the order A06, C06, J11, and M09. As the data are further analyzed and used in modeling, this relationship between sites will be further defined.

Table 38. Summary of Extreme Soil Moisture Data in the Top 51 Inches of Watershed Soils

Site	Maximum Soil Moist. (In.)	Minimum Soil Moist. (In.)	Range (In.)
C06	16.66	13.29	3.37
M09	18.35	16.50	1.85
J11	17.59	14.13	3.46
A06	15.93	11.58	4.35

9. Infiltration

The rainfall simulator-infiltrometer system described in the Experimental Design and Procedures section was utilized to obtain infiltration data at four different sites. Data from three of the prominent soils at Watershed C06 (Coshocton, Gilpin, and Dekalb) and from the Rayne soil at the North Appalachian Experimental Watershed (near Watershed A06) are listed in Tables 39-42. The data are presented graphically in Figures 47-50.

Soil moisture was gravimetrically determined using samples collected immediately before and after the infiltration run. These data are also in Tables 39-42 and are plotted as an insert in Figures 47-50. The values were only representative of the moisture trends since sampling was extremely difficult at the wooded sites.

Prior to the initiation of surface runoff at two of the C06 sites (Coshocton and Gilpin soils), a significant amount of water was retained by the site, and a "shingle" leaf runoff (significant for

Table 39. Infiltration and Soil Moisture Data for Coshocton Soil on Watershed C06.

Site: Location IA on Figures 7 and 11

Date: October 28, 1976

Cover: Wooded site with six ½-inch (dia.) bushes; five 1-inch bushes; two 2-inch trees; one 3-inch tree; 1.5 inches of duff and 2 inches of leaves.

Slope: 31 percent

Soil Moisture			Infiltration[3]	
Depth (In.)	Before Run[1] (%)	After Run[2] (%)	Time (Min.)	Rate (In./Hr.)
0-1	29.7	38.2	0	2.00
1-2	16.2	29.2	5.0	1.93
2-3	15.4	22.2	9.5	1.84
3-4	14.9	22.6	14.5	1.89
4-5	15.0	17.4	18.0	1.73
5-6	15.6	17.2	20.5	1.56
6-8	17.2	16.7	24.5	1.24
8-10	19.0	18.8	29.5	1.02
10-12	19.0	19.8	34.5	.91
12-14	20.8	19.1	39.5	.86
14-16	19.5	21.2	44.5	.75
16-18	17.8	17.2	49-53[4]	-
18-24	17.5	-	64.5	.80
			69.5	.80
			74.5	.75

Table 39. (Cont'd) Infiltration and Soil Moisture Data for Coshocton Soil on Watershed C06.

Soil Moisture			Infiltration	
Depth (In.)	Before Run (%)	After Run (%)	Time (Min.)	Rate (In./Hr.)
			84.5	.75
			97.0	.66
			116.0	.64
			137.0	.58
			157.0	.56
			167.0	.58

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[1] Average of 2 gravimetric samples taken outside plot.
[2] Average of 3 gravimetric samples taken at end of run.
[3] Application rate of 2.00 In./Hr. for 3¼ hrs. Air temperature about 40°F.
[4] Water flow to modules interrupted.

Table 40. Infiltration and Soil Moisture Data for Gilpin Soil on Watershed C06

Site: Location IB on Figures 7 and 11

Date: November 2, 1976

Cover: Wooded with small brush on plots; 1 to 1.5 inches of duff and 3 layers of new leaves.

Slope: 30 percent

Soil Moisture[1]			Infiltration[4]	
Depth (In.)	Before Run[2] (%)	After Run[3] (%)	Time (Min.)	Rate (In./Hr.)
Duff	84.3	-	1	2.50
0-1	36.2	-	4	2.36
1-2	32.0	-	11	2.28
2-3	28.7	-	21	2.25
3-4	27.0	-	31	2.26
4-5	22.6	-	41	2.28
5-6	22.1	-	56	2.12
6-8	17.1	-	76	1.91
8-10	15.6	-	96	1.70
10-12	17.1	-	116	1.57
			136	1.52
			156	1.39
			191	1.35
			196	1.36
			202	1.32
			208	1.32

[1] Rainfall of .5 inch occurred on 10-30-76.

[2] Average of 3 gravimetric samples just outside plot visibly moist to depth of 14 inches. (Two values discarded.)

[3] Moisture determinations not adequate to determine moisture changes.

[4] Application rate of 2.5 inches per hour for 3.5 hours. Air temperature 40°F.

Table 41. Infiltration and Soil Moisture Data for Dekalb Soil on Watershed C06

Site: Location IC on Figures 7 and 11

Date: November 1976

Cover: Wooded; small brush on plot; 4-5 layers of leaves; and 1-1.5 inches of duff

Slope: 40 percent

	Soil Moisture[1]		Infiltration[4]	
Depth (In.)	Before Run[2] (%)	After Run[3] (%)	Time (Min.)	Rate (In./Hr.)
Duff	65.1	-	0	2.50
0-1	18.7	33.0	1	2.49
1-2	16.4	28.1	2.5	2.42
2-3	10.3	15.4	3.5	2.20
3-4	13.1	18.3	5.0	2.17
4-5	12.3	11.7	8	2.13
5-6	11.8	14.4	15	2.16
6-8	11.5	15.9	25	2.15
8-10	10.1	14.5	35	2.15
10-12	11.5	-	45	2.15
12-14	10.6	-	55	2.15

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[1] Soil very difficult to sample due to large number of stones.

[2] Average of 2 gravimetric samples taken outside plot.

[3] Average of 3 gravimetric samples taken outside plot.

[4] Application rate of 2.5 In./Hr. for 3 hours. Water apparently lost from plot due to rock bed. Runoff from leaf surface. Sunny, with air temperature in 50's.

Table 42. Infiltration and Soil Moisture Data for Rayne Soil on Watershed 129 at North Appalachian Experimental Watershed.

Site: Located about 1/2 mile to northeast of Watershed A06.

Date: October 19, 1976

Cover: Grass, pasture-height about 2 inches

Slope: 15 percent

	Soil Moisture		Infiltration[3]	
Depth (In.)	Before Run[1] (%)	After Run[2] (%)	Time (Min.)	Rate (In./Hr.)
0-1	14.2	29.9	5	1.00
1-2	15.1	19.3	18	1.00
2-3	16.9	16.9	27	0.93
3-4	12.5	15.9	29	0.86
4-5	11.4	16.3	35	0.78
5-6	11.3	11.2	45	0.57
6-7	10.9	12.1	55	0.56
7-8	12.2	12.5	65	0.54
8-9	11.7	13.4	75	0.54
9-10	12.4	11.4	85	0.51
			95	0.46
			105	0.48
			115	0.48
			125	0.46

[1] Average of 3 gravimetric samples just outside plot.
[2] Average of 3 gravimetric samples taken at end of run.
[3] Application rate of 1 inch for 2¼ hours.

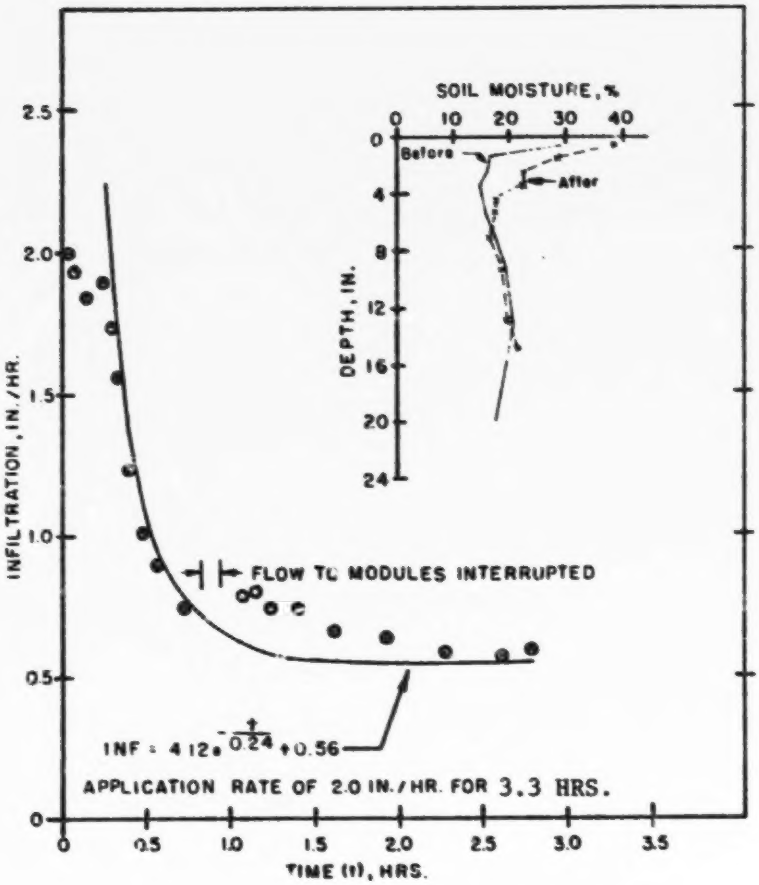

Figure 47. Infiltration and Soil Moisture for Coshocton Soil on Watershed C06

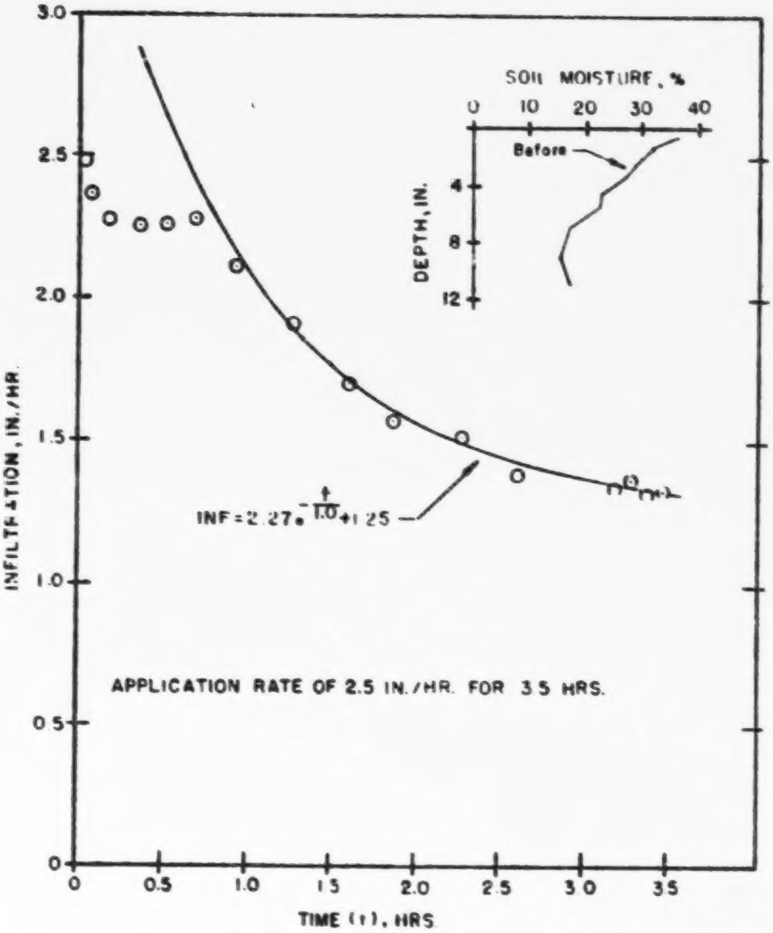

Figure 48. Infiltration and Soil Moisture for Gilpin Soil on Watershed C06

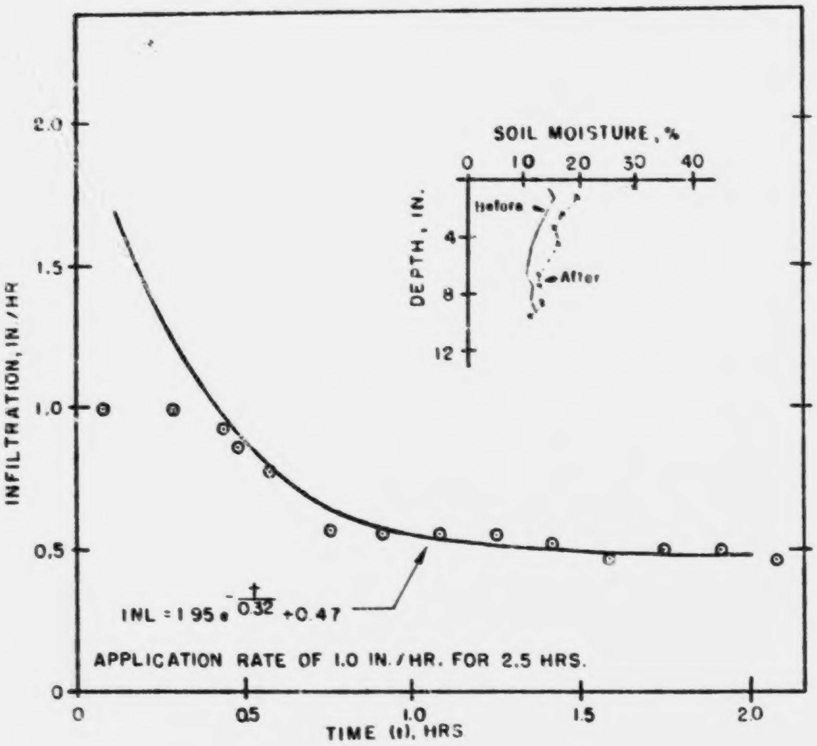

Figure 49. Infiltration and Soil Moisture for Rayne Soil on Watershed 129 at North Appalachian Experimental Watershed

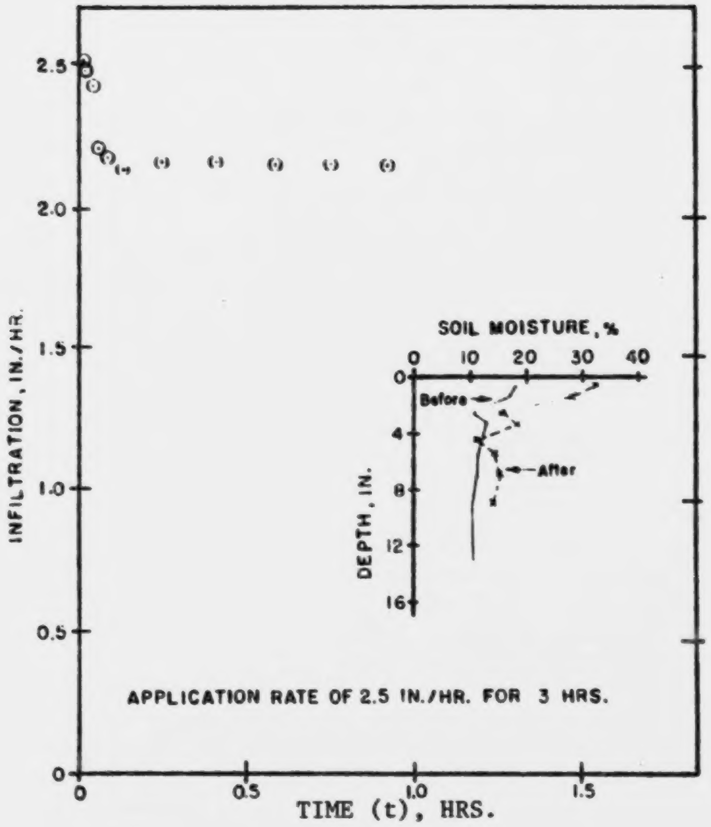

Figure 50. Infiltration and Soil Moisture for DeKalb Soil on Watershed C06

small plots) developed on these wooded sites. This runoff ranged from 0.16 to 0.24 inches per hour. At the Dekalb soil site this leaf runoff amounted to about 0.34 inches per hour, and the infiltration capacity of the site was not reached with a constant application rate of 2.5 inches per hour for three hours. It is likely, however, that water was lost from behind the cut-off wall through root channels.

The infiltration capacity values for the Coshocton, Gilpin, and Rayne soils were consistent. except for a break in the curve for the Coshocton soil resulting from an interruption of water application, and are representable by a three parameter equation. This equation, representing an analogous resistance - capacitance electric circuit, is of the form

$$\text{Inf. Rate (In./Hr.)} = Ae^{-\frac{t}{C}} + B,$$

where A is the maximum unadjusted rate, C is the time constant, and B is a steady state term. For infiltration, the first term represents the transient capillary force that is highly significant during the initial infiltration phase and the second term can be visualized as the equilibrium infiltration or the saturated hydraulic conductivity of the soil. At application rates of 2.0 and 2.5 inches per hour, the equilibrium rates of 0.56 and 1.25 inches per hour (Figures 47 and 48) were reached in about 3 and 4 hours for the Coshocton and Gilpin soils, respectively.

The infiltration equation presented above, similar to an equation presented by Horton (1933), can be expressed in terms of soil water volumes, a time constant for the transient phase, and a constant term. These values can be easily obtained by use of the infiltrometer, thereby affording an assessment of the runoff generation expected from different hydrological inputs for a variety of surface conditions.

10. Spring Discharge

Spring discharge data were collected to determine the magnitude of the load of water quality constituents supplied by a monitored seep to base flow, and to verify simulated seepage flow obtained by ground-water modeling.

Breakpoint spring flow stage data were tabulated with at least one reading per day at midnight and were converted to flow rates. The springs were destroyed when mining began.

The springs exhibited a long-term trend of slowly decreasing flow at the C06 and M09 sites. Flow at the M09 site ceased in the fall. At least two factors caused this decrease and cessation of flow:

1. The dry season of the year.

2. The watersheds adjacent to the study watershed were being mined causing the ground-water table to drain to the mined side of the watershed.

The C06 spring discharge increased slightly before it was destroyed. Table 43 shows the monthly volumes of water that flowed from each spring and the average daily flow rates. The A06 spring discharged at a higher rate than either C06 or M09, about 8 times their average daily rates. Table 44 shows the summary of extreme flow rates for the springs. The M09 spring was dry for much of the time and was possibly affected by mining on the back side of the watershed.

11. Runoff

Mining commenced on Watersheds C06 and M09 before data for a full year were obtained. Premining data were not obtained for the late fall for C06, and for the winter and early spring for the M09 site. The monthly yield runoff hydrographs of all outlet and small watershed measuring stations are shown in Figures 51 and 52. Table 45 gives the A06 outlet data from which Figure 51 was derived. The monthly percent difference shows the variation of the short-term record from the long-term record.

The long-term average and observed monthly flows (water yields) for A06 are given in Table 45, along with percent departure from average monthly flows. The averages were obtained for the period from 1967 through 1977, except for a three-year break in the record from July, 1972 through June, 1975. The water yield for the two and one-half years based on data obtained since July 1975 were higher than average for half of the record. The time distribution of flow for the whole record (Figure 51) shows how the runoff pattern varies from the average pattern. The largest deviation was +312 percent in December, 1977 and the smallest was -5 percent in July, 1975.

The total water yield and precipitation for each study watershed, including peak flows and causative precipitation, are summarized in Table 46. Peak flow hydrographs and the causative precipitation patterns are shown in Figures 53-56.

The peak flow rate for Watershed C06 occurred after an extended dry period of zero flow for nine days. As a result, much of the rain was abstracted to satisfy the depleted soil moisture storage. This partially accounts for the low 7 percent runoff coefficient for this storm (Figure 53).

The M09 hydrographs in Figure 54 resulted from rainfall on a moderately dry soil. The large and small watershed hydrographs in Figure 54 show the outlet peak lags the small watershed peak by 8 minutes.

Table 43. Summary of Monthly Volumes of Premining Spring Discharge Data (ft^3 of water) and Average Gallons Per Day

Site	Year and Month												Total Flow ft^3/mo.	Avg. Flow ft^3/day
	1975													
	1	2	3	4	5	6	7	8	9	10	11	12		
C06							--	--	--	--	--	--		
M09							--	--	--	--	--	--		
A06							104M	3080	10806	14506	9716	19359		
	1976													
C06	--	2354M	8473	4432	3541	1801	2033	3147	1608	1607	920	1292		
M09	--	--	--	272M	4251	3888	4559	3504	1128	737	13	0.0		
A06	30901	45964	53239	45393	26015	18070	26403	19552	14853	14196	14110	14196		
	1977													
C06	216M	--	--	--	--	--	--	--	--	--	--	--	31,424	99.8
M09	0.0	0.0	0.0	0.0	0.0	--	--	--	--	--	--	--	18,352	98.6*
A06	14196	17452	45804	51491	36666	16416	15158	14196	18903	28165	36038	61194	736,142	805.0

M - Number based on missing data in the record

* - Average for period April through October, 1976.

Table 44. Summary Extremes of Premining Spring Discharge Data

Site	Minimum Discharge (cfs)	Maximum Discharge (cfs)	Range of Average Daily Discharge (cfs)
C06[1]	0.0003	0.012	0.0003 - 0.0052
M09[2]	0.0	0.0214	0.0 - 0.0032
A06[3]	0.0008	0.0712E	0.0008 - 0.0444

E - Estimated flow
[1] Spring located at outcrop of No. 6 coal
[2] Spring located at outcrop of No. 9 coal
[3] Spring located near outcrop of No. 4 coal

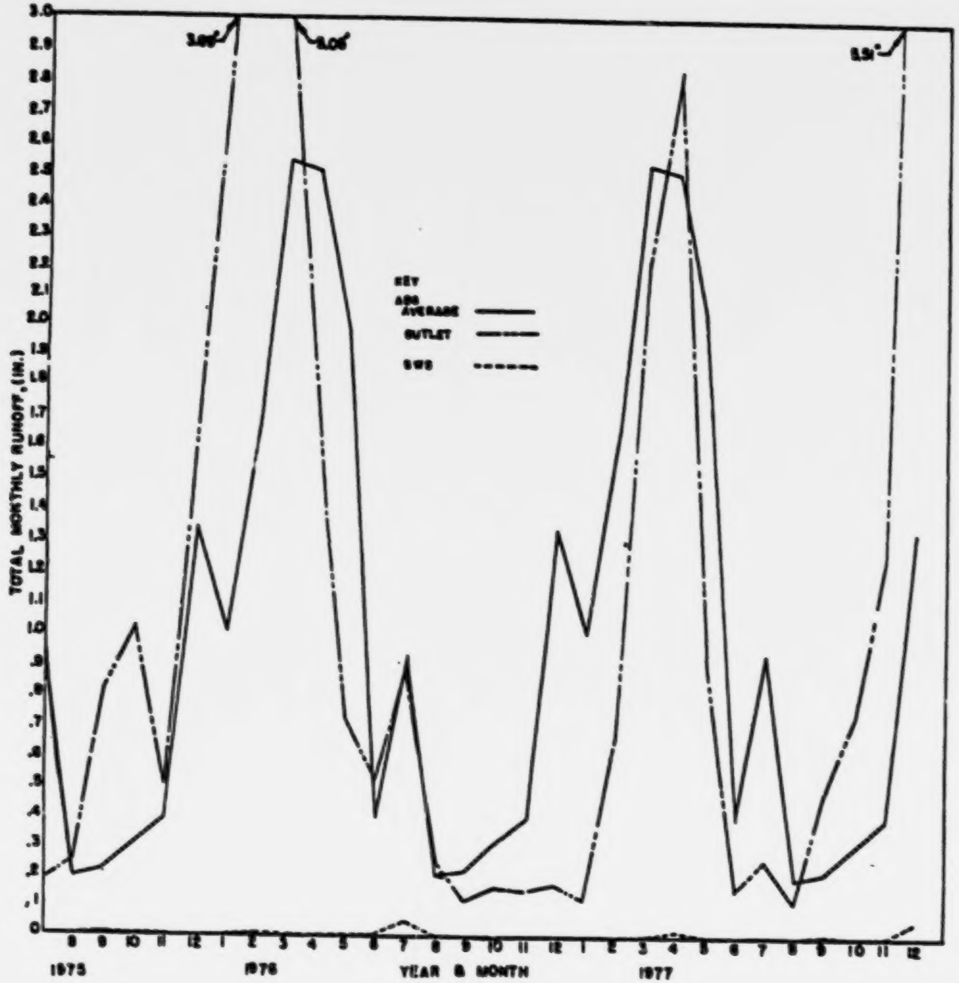

Figure 51. Time Distributions of Monthly Yields for Unmined Watershed A06

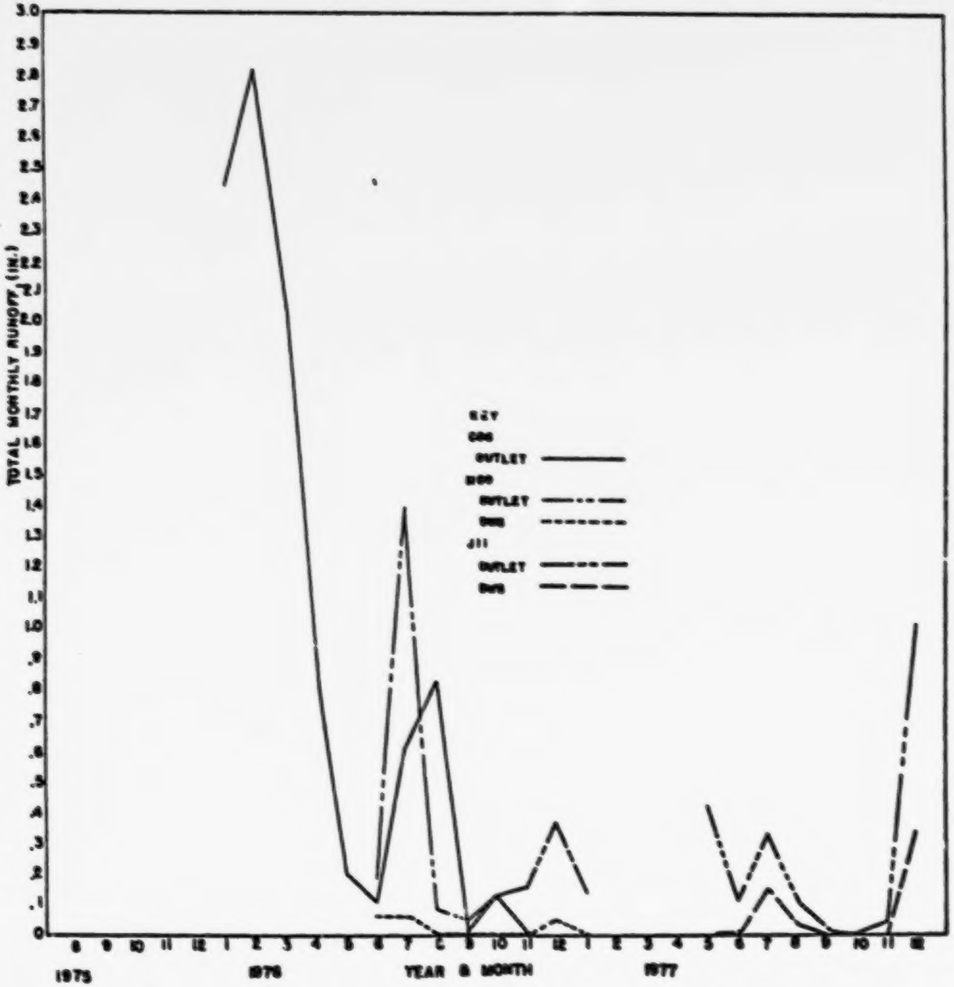

Figure 52. Time Distributions of Monthly Water Yields for Watersheds C06, M09, and J11

Table 45. Monthly Long-Term Average and Observed Runoff for Watershed A06

Item	Year and Month											
	1975							1976				
	7	8	9	10	11	12	Total	1	2	3	4	5
A06 Avg. (In.)	.9474	.1955	.2244	.3104	.3944	1.3356	3.4077	1.0179	1.6533	2.5390	2.5075	1.9644
A06 Rec. (In.)	.1813	.2505	.8271	1.0356	.5028	1.5269	4.3242	2.8532	3.6944	3.0587	1.7082	.7382
% Diff.	-81	+28	+269	+234	+27	+14	+27	+180	+123	+20	-32	-62

	1976								1977		
	6	7	8	9	10	11	12	Total	1	2	3
A06 Avg. (In.)	.3985	.9474	.1955	.2244	.3104	.3944	1.3356	13.4883	1.0179	1.6533	2.5390
A06 Rec. (In.)	.5242	.8999	.2560	.1119	.1564	.1539	.1737	14.3287	.1191	.6498	2.2040
% Diff.	+32	-5	+31	-50	-50	-61	-87	+6	-88	-61	-13

	1977									
	4	5	6	7	8	9	10	11	12	Total
A06 Avg. (In.)	2.5075	1.9644	.3985	.9474	.1955	.2244	.3104	.3944	1.3356	13.4883
A06 Rec. (In.)	2.8539	.9548	.1508	.2646	.1230	.4841	.7370	1.2494	5.5084	15.2989
% Diff.	+14	-51	-62	-72	-37	+116	+137	+217	+312	+13

Table 46. Summary of Runoff Data.

Site	Total Precip. (In.)	Total Flow (In.)	Yield[1]	Peak Event					
				Date	Flow (cfs)	Yield for Event (In.)	Causative Precip.(In.)	Yield[1]	Antecedent Conditions
C06									
Outlet	33.54	10.19	30	7/08/76	5.86	0.18	1.65	11	Dry
M09									
Outlet	20.21	2.44	12	7/11/76	81.95	1.2	3.02	40	Moderately Dry
Small WS	20.93	.77	4	7/11/76	6.90	0.58		19	
J11									
Outlet	27.14	2.07	8	7/21/77	6.31	0.14	1.93	7	Dry
Small WS	25.06	.53	2	7/21/77	1.67	0.14		7	
A06									
Outlet	95.32	33.95	36	7/11/76	13.80	0.50	1.75	29	Wet
Small WS	87.95	.18	<1	7/11/76	.181	0.05		2	

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[1] Percent of Precipitation

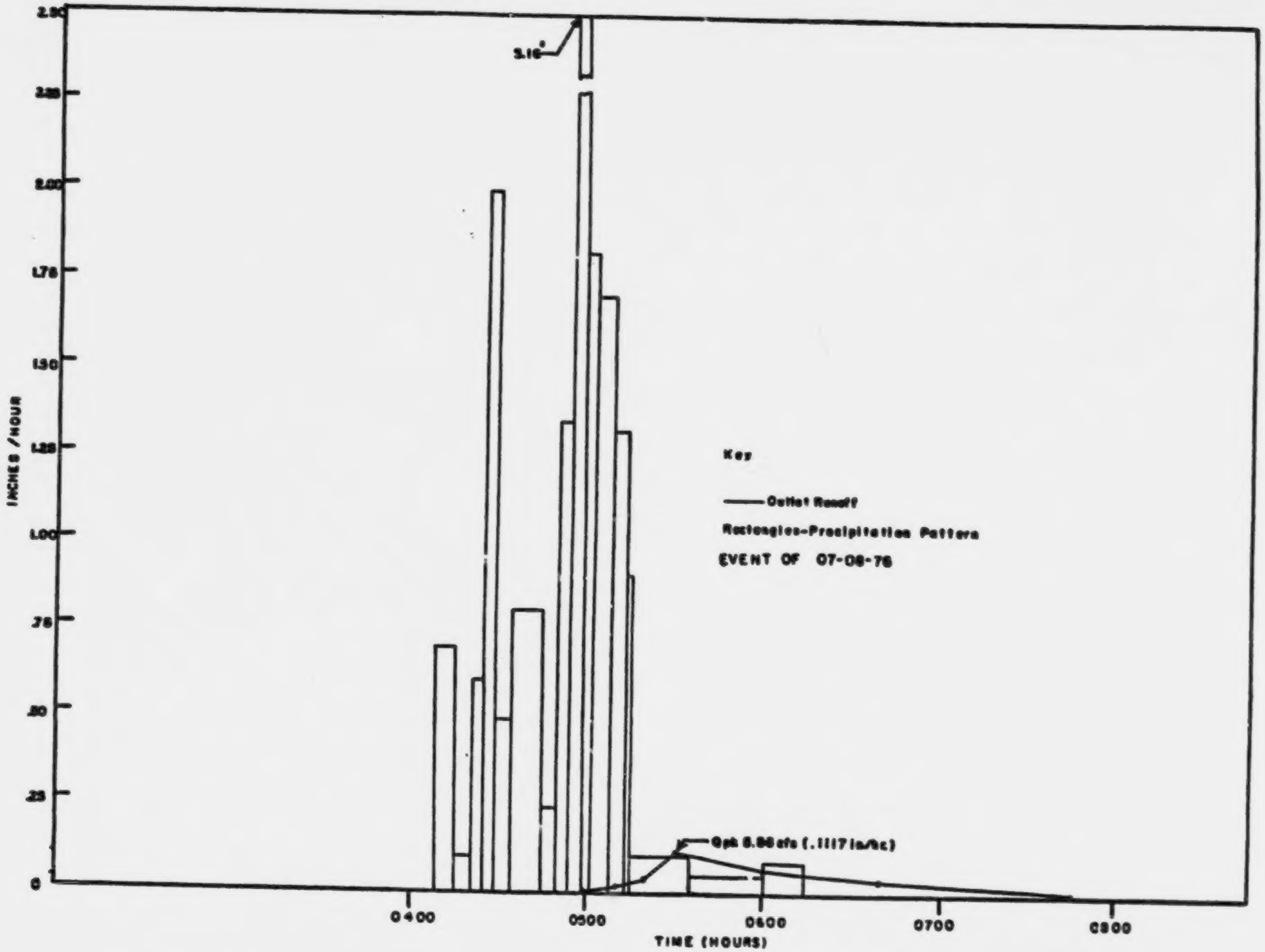

Figure 53. Runoff Hydrograph and Causative Precipitation for the Peak Flow Hydrograph for Watershed C06

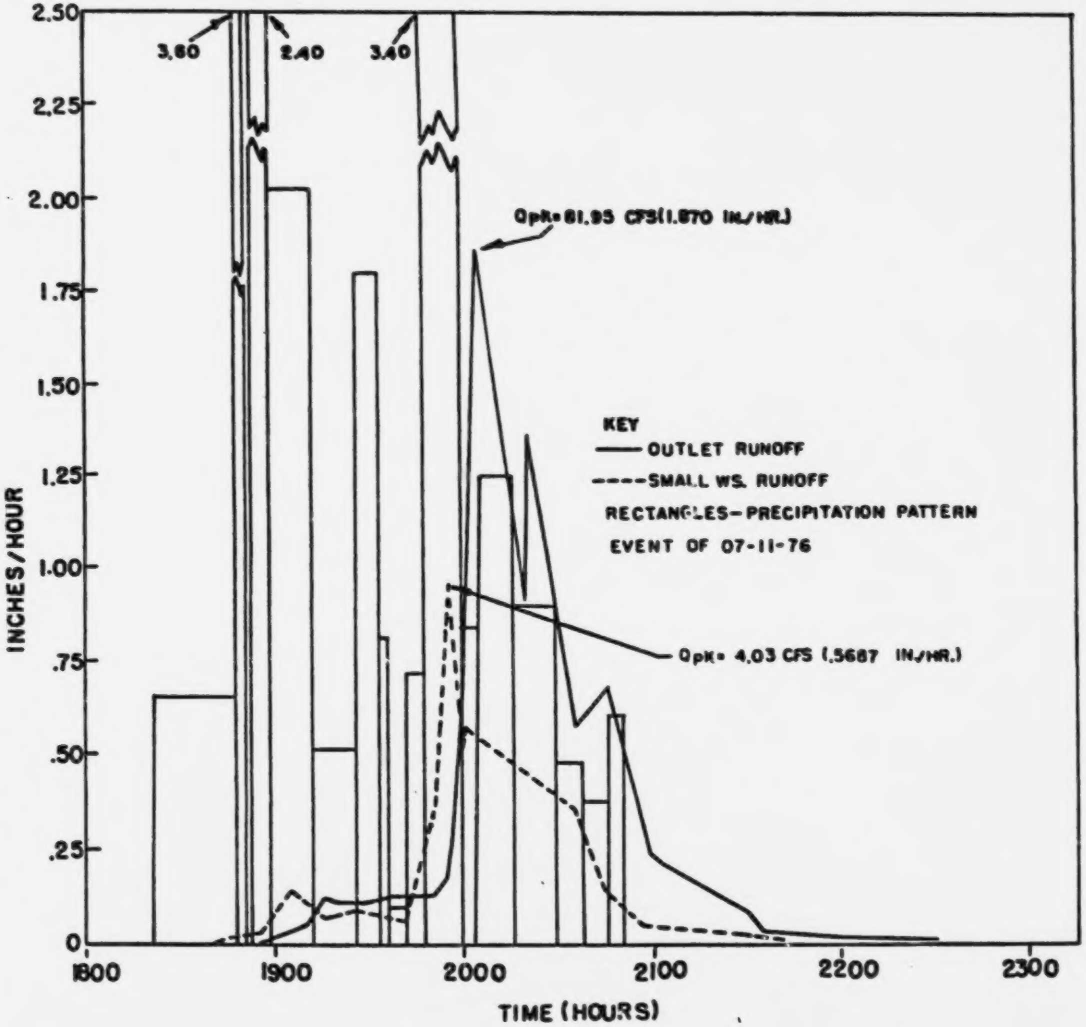

Figure 54. Runoff Hydrographs and Causative Precipitation for the Peak Flow Hydrographs for Watershed M09

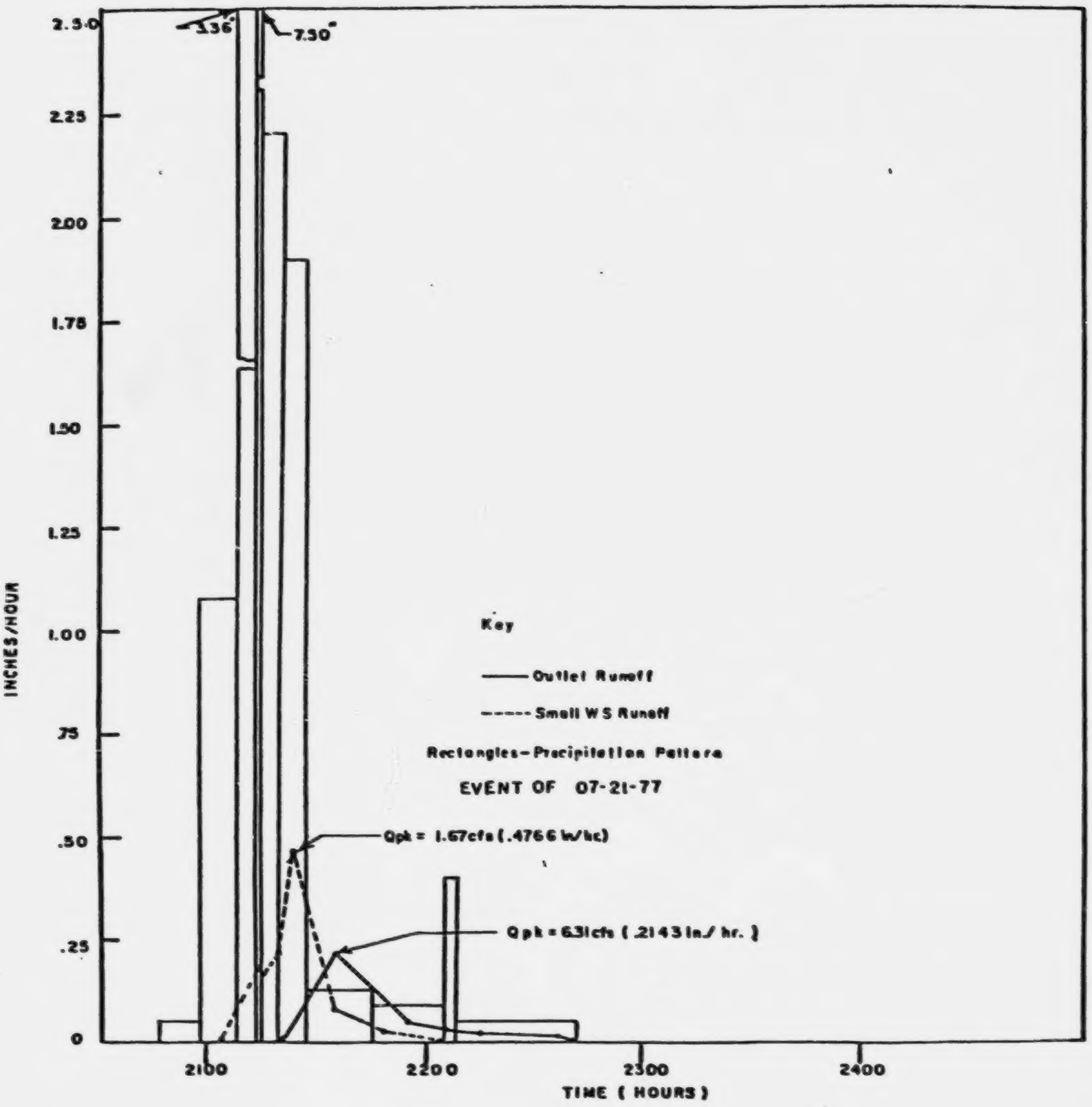

Figure 55. Runoff Hydrographs and Causative Precipitation for Peak Flow Hydrographs for Watershed J11

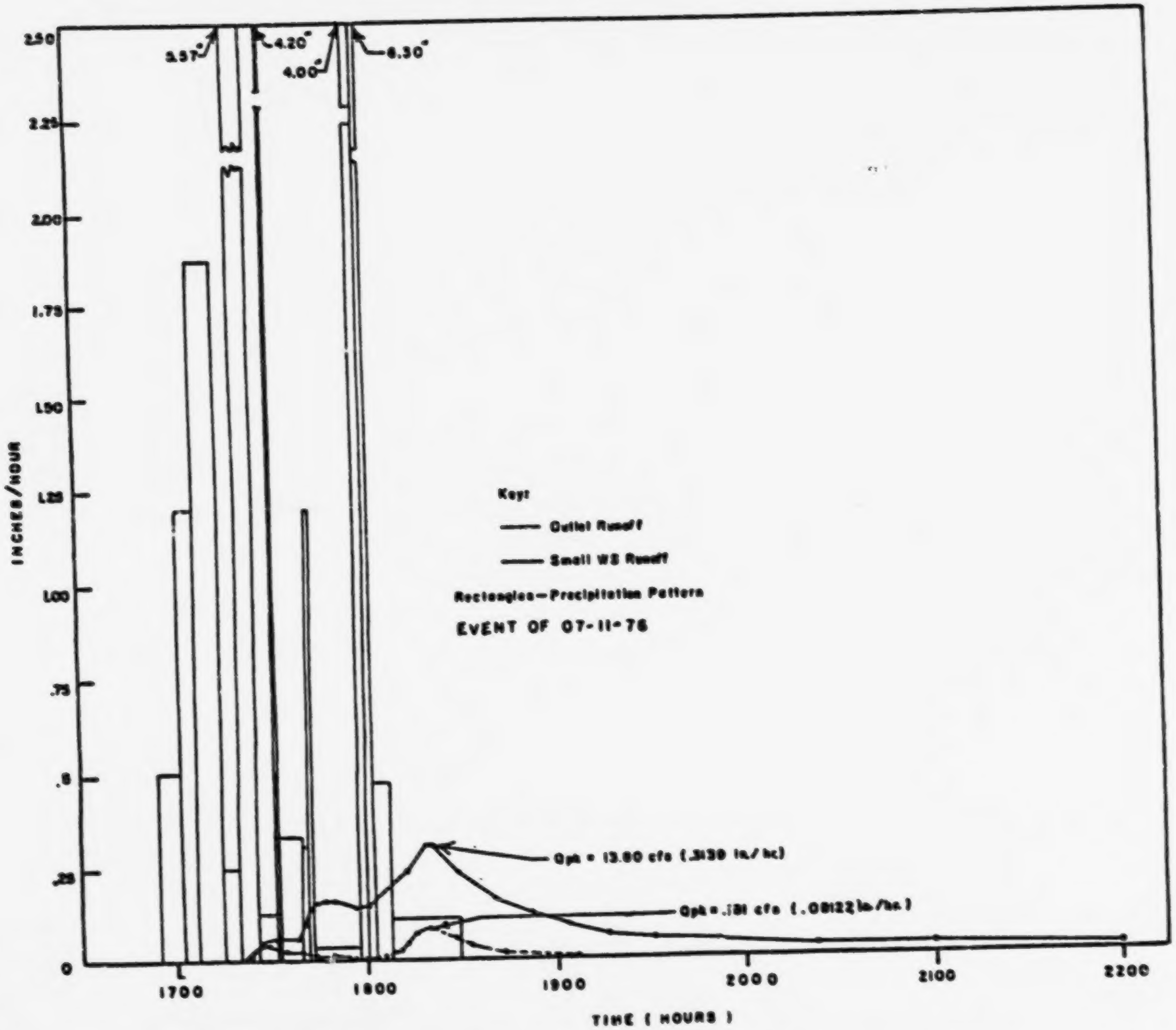

Figure 56. Runoff Hydrographs and Causative Precipitation for the Peak Flow Hydrographs for Unmined Watershed A06

The J11 hydrographs in Figure 55 resulted from rainfall on dry soils. There was no flow for one day prior to this event; a rare occurrence. Both watersheds yielded the same runoff in terms of inches over different size areas. The soils were essentially the same for the watersheds and this helps explain the similar yields. The reason for the higher peak yield for the small watershed may have been due to the presence of a seep in the small watershed about 100 feet upstream from the weir. Figure 4 shows the outcrop of the number 11 coal, the source of the seep.

The hydrographs for A06 resulted from precipitation on moderately dry to wet soils (Figure 56). The difference between yields for the two A06 sites (Table 46) was due to the predominance of a well-drained Dekalb soil in the small watershed and the occurrence of return flow (seeps and springs) above the outlet weir on the large watershed. The A06 hydrographs are shown to have peaked about the same time, indicating a possible error in the timing of the runoff record.

The short period of runoff records at the C06 and M09 sites during the premining phase necessitates a deterministic modeling approach for assessing premining hydrology. Data will become sufficient, however, at the A06 and J11 sites for developing and evaluating such a model. The model can be refined for application to the C06 and M09 sites by incorporating the short term record and by relying on soil moisture data for a refined definition of the hydrologic response of the separate hydrologic units in the watersheds.

IV. SURFACE-WATER QUALITY

A. Experimental Procedure

Surface-water samples (base-flow and runoff) from four of the study watersheds (C06, M09, J11, and A06), Figure 1, were obtained to determine various water quality parameters. These samples were collected either by hand (grab sample) or, in a few instances, by automatic sampling devices. The frequency of sampling varied from watershed to watershed, depending upon the number of runoff events. The collected runoff and base-flow samples were treated and prepared for analyses according to the procedures which are schematically presented in Figure 57. Among the reported parameters, color, pH, flow rate, and temperature of water were measured in the field, and the remaining parameters were determined in the laboratory.

The procedures used for determination of the various water quality parameters were as follows: standard methods (A.P.H.A., 1975) for acidity, alkalinity, bicarbonate, carbon dioxide, chloride, color, hardness, nitrate, pH, phenol, sulfate, suspended solids, and dissolved solids; inductively coupled argon plasma method for aluminum, antimony, barium, cadmium, calcium, copper, iron, lead, magnesium, manganese, nickel, phosphorus, silver, sodium, strontium, and zinc; electrode method for ammonia, cyanide, fluoride, and hydrogen sulfide; atomic absorption for arsenic (graphite rod), and mercury (flameless); diphenylcarbazide method (Brown et al, 1970) for hexavalent chromium; and fluorometric method (Olson et al, 1975) for selenium.

In addition to runoff and base-flow samples, monthly precipitation samples from M09 and J11 sites were obtained and analyzed for aluminum, antimony, barium, bicarbonate, cadmium, calcium, copper, hydrogen sulfide, iron, lead, magnesium, manganese, nickel, nitrate nitrogen, pH, phosphorus, silver, sodium, specific conductance, strontium, sulfate, and zinc.

Since the quantities of sediment collected for each runoff or base-flow event at a given site were too small for the complete analyses, the sediment samples obtained from each site (C06, M09, A06, and J11) from different events were combined until sufficient quantities were collected from a given site for chemical analyses. Thus, the reported values on the concentration of different parameters determined for the sediment fractions are for composite samples.

B. Results and Discussion

The range and average values for different surface-water quality parameters for base-flow and runoff water samples from unmined Watersheds C06, M09, J11 and A06 are shown in Tables 47-72. In addition to these

Figure 57. Schematic of Procedures for Treatment of Water Samples

- Water + Sediment Samples
  - 1. Raw Untreated (Sediment undisturbed)
    - 1.1 Aliquot for acidity, alkalinity, bicarbonate, and CO_2
    - 1.2 Aliquot for nitrate and ammonia N (store at 0-4C)
    - 1.3 Aliquot for phenol (store in glass bottle at 4C)
    - 1.4 Aliquot for cyanide (treat with NaOH and store at 4C)
    - 1.5 Aliquot for sulfide (treat with NaOH and store at 4C)
  - 2. Raw Untreated (Sediment suspended)
    - 2.1 Aliquot for suspended solids
  - 3. Raw Untreated (Centrifuged and filtered through .45 um)
    - 3.1 Water phase
      - 3.1.1 Aliquot for $SO_4^=$, Cl^-, and F^-
      - 3.1.2 Aliquot for dissolved solids
      - 3.1.3 Acidify the remaining H_2O with HNO_3
        - 3.1.3.1 Aliquot for Al, Sb, Ba, Cd, Ca, Cr, Fe, Pb, Mg, Mn, Ni, P, Ag, Na, Sr, and Zn
        - 3.1.3.2 Aliquot for Hg
        - 3.1.3.3 Aliquot for As
        - 3.1.3.4 Aliquot for Cr^{+6}
        - 3.1.3.5 Aliquot for Se
    - 3.2 Sediment phase
      - 3.2.1 Pass through a 2 mm non-metallic sieve
        - 3.2.1.1 Aliquot for Hg
        - 3.2.1.2 Aliquot for $SO_4^=$
        - 3.2.1.3 Aliquot for TOC
        - 3.2.1.4 Aliquot for Al, Cd, Ca, Cu, Fe, Pb, Mg, Mn, Ni, P, Na, Sr, and Zn
        - 3.2.1.5 Aliquot for pH

Table 47. **Analytical Results for Base-Flow Water Samples (Grab, 5) from Weir at C06 (Unmined) Watershed Site.**

Parameter	Units	Range		Average
Acidity	meq/l	0.06	0.19	0.12
Alkalinity[1]	mg/l	41	60	50
Aluminum	µg/l	33	294	125
Ammonia (N)	mg/l	<0.01	0.03	<0.02
Antimony	µg/l	<21	43	<29
Arsenic	µg/l	<1		<1
Barium	µg/l	32	53	40
Bicarbonate	mg/l	50	73	61
Cadmium	µg/l	<1	8	<4
Calcium	mg/l	19.9	26.2	23.1
Carbon Dioxide	mg/l	3.1	4.8	4.1
Chloride	mg/l	1.3	2.3	1.9
Chromium	µg/l	<10	12	<11
Color[2]		10	20	15
Copper	µg/l	<2	4	<3
Cyanide	mg/l	<0.01	0.06	<0.03
Fluoride	mg/l	0.06	0.10	0.08
Hardness[3]	mg/l	80	109	94
Hydrogen Sulfide	mg/l	<0.01		<0.01
Iron	µg/l	13	460	183
Lead	µg/l	<15	33	<23
Magnesium	mg/l	7.4	10.5	8.8
Manganese	µg/l	10	360	102
Mercury	µg/l	<1	8	<2
Nickel	µg/l	<12	40	<24
Nitrate (N)	mg/l	<0.1	2.2	<0.6
pH (Field)		*		
Phenols	µg/l	<4	7	<5
Phosphorus	mg/l	<0.03	<0.05	<0.04
Selenium	µg/l	0.1	0.3	0.2
Silver	µg/l	<3	5	<4
Sodium	mg/l	3.8	4.7	4.3
Strontium	µg/l	62	90	77
Sulfate	mg/l	34	43	39
Temperature	C°	2	21	12
Zinc	µg/l	3	74	20
Flow Rate	CFS	0.0035	0.1268	0.0442
Suspended Solids	mg/l	none	978	247
Dissolved Solids	mg/l	114	141	129

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[1] As calcium carbonate
[2] 0-500 color units
[3] Calcium and magnesium
* Not measured

Table 48. Analytical Results for Runoff Water Samples (Grab, 4) from Weir at C06 (Unmined) Watershed Site.

Parameter	Units	Range		Average
Acidity	meq/l	0.08	0.13	0.10
Alkalinity[1]	mg/l	9	19	14
Aluminum	μg/l	55	501	239
Ammonia (N)	mg/l	0.04	0.11	0.07
Antimony	μg/l	<22	<26	<23
Arsenic	μg/l	<1		<1
Barium	μg/l	19	49	27
Bicarbonate	mg/l	11	23	17
Cadmium	μg/l	<2		<2
Calcium	mg/l	9.0	11.5	10.0
Carbon Dioxide	mg/l	1.4	5.7	3.6
Chloride	mg/l	<0.1	0.6	<0.4
Chromium	μg/l	<10	<12	<11
Color[2]		4-5	400	180
Copper	μg/l	1	18	8
Cyanide	mg/l	<0.01	0.01	<0.01
Fluoride	mg/l	0.08		0.08
Hardness[3]	mg/l	35	45	39
Hydrogen Sulfide	mg/l	<0.01		<0.01
Iron	μg/l	36	308	209
Lead	μg/l	<14	<15	<15
Magnesium	mg/l	3.0	3.9	3.3
Manganese	μg/l	20	277	97
Mercury	μg/l	<1		<1
Nickel	μg/l	<6	<18	<9
Nitrate (N)	mg/l	0.7	1.7	1.2
pH (Field)		*		
Phenols	μg/l	6	9	8
Phosphorus	mg/l	<0.03	0.24	<0.08
Selenium	μg/l	0.2	0.4	0.3
Silver	μg/l	<2	<3	<3
Sodium	mg/l	1.0	1.8	1.4
Strontium	μg/l	32	45	37
Sulfate	mg/l	20	24	22
Temperature	C°	18	22	19
Zinc	μg/l	2	71	25
Flow Rate	CFS	0.8043	4.769	2.107
Suspended Solids	mg/l	97	1640	870
Dissolved Solids	mg/l	66	100	85

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[1] As calcium carbonate

[2] 0-500 color units

[3] Calcium and magnesium

* Not measured

Table 49. Analytical Results for Base-Flow Water Samples (Grab, 1) from Reservoir at C06 (Unmined) Watershed Site.

Parameter	Units	Quantity
Acidity	meq/l	0.10
Alkalinity[1]	mg/l	51
Aluminum	µg/l	37
Ammonia (N)	mg/l	<0.01
Antimony	µg/l	<27
Arsenic	µg/l	<1
Barium	µg/l	20
Bicarbonate	mg/l	62
Cadmium	µg/l	<4
Calcium	mg/l	32.0
Carbon Dioxide	mg/l	5.0
Chloride	mg/l	2.8
Chromium	µg/l	<10
Color[2]		40
Copper	µg/l	5
Cyanide	mg/l	<0.01
Fluoride	mg/l	0.13
Hardness[3]	mg/l	125
Hydrogen Sulfide	mg/l	<0.01
Iron	µg/l	23
Lead	µg/l	29
Magnesium	mg/l	10.9
Manganese	µg/l	462
Mercury	µg/l	<1
Nickel	µg/l	29
Nitrate (N)	mg/l	<0.1
pH (Field)		*
Phenols	µg/l	<4
Phosphorus	mg/l	0.35
Selenium	µg/l	0.7
Silver	µg/l	<3
Sodium	mg/l	3.8
Strontium	µg/l	110
Sulfate	mg/l	69
Temperature	C°	1
Zinc	µg/l	20
Flow Rate	CFS	0.006
Suspended Solids	mg/l	none
Dissolved Solids	mg/l	160

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[1] As calcium carbonate

[2] 0-500 color units

[3] Calcium and magnesium

* Not measured

Table 50. **Analytical Results for Base-Flow Water Samples (Grab, 5) from Large Weir at M09 (Unmined) Watershed Site.**

Parameter	Units	Range		Average
Acidity	meq/l	0.16	0.63	0.30
Alkalinity[1]	mg/l	116	157	139
Aluminum	µg/l	<14	191	<56
Ammonia (N)	mg/l	<0.01	<0.04	<0.02
Antimony	µg/l	<11	38	<26
Arsenic	µg/l	<1	<2	<2
Barium	µg/l	23	80	59
Bicarbonate	mg/l	142	191	169
Cadmium	µg/l	<2	<4	<3
Calcium	mg/l	46.4	86.9	64.9
Carbon Dioxide	mg/l	0.6	28.8	14.3
Chloride	mg/l	5.4	11.6	9.1
Chromium	µg/l	<10	<12	<11
Color[2]		2-3	5	4
Copper	µg/l	1	4	<3
Cyanide	mg/l	<0.01	0.01	<0.01
Fluoride	mg/l	0.08	0.18	0.15
Hardness[3]	mg/l	185	322	246
Hydrogen Sulfide	mg/l	<0.01		<0.01
Iron	µg/l	7	140	46
Lead	µg/l	<13	33	<18
Magnesium	mg/l	14.8	25.5	20.3
Manganese	µg/l	1	57	24
Mercury	µg/l	<1	3	<2
Nickel	µg/l	<6	56	<27
Nitrate (N)	mg/l	<0.1	1.3	<0.6
pH (Field)		*		
Phenols	µg/l	<4	7	<5
Phosphorus	mg/l	<0.02	0.09	<0.04
Selenium	µg/l	0.2	0.3	0.2
Silver	µg/l	<2	5	<3
Sodium	mg/l	3.9	6.7	5.6
Strontium	µg/l	234	397	307
Sulfate	mg/l	31	56	43
Temperature	C°	1	21	15
Zinc	µg/l	4	64	18
Flow Rate	CFS	0.0045	0.0524	0.0201
Suspended Solids	mg/l	none	415	157
Dissolved Solids	mg/l	129	281	225

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[1] As calcium carbonate

[2] 0-500 color units

[3] Calcium and magnesium

* Not measured

Table 51. Analytical Results for Runoff Water Samples (Grab, 2) from Large Weir at M09 (Unmined) Watershed Site.

Parameter	Units	Quantity		Average
		#1	#2	
Acidity	meq/l	0.09	0.06	0.08
Alkalinity[1]	mg/l	202	40	121
Aluminum	µg/l	175	580	378
Ammonia (N)	mg/l	0.02	0.29	0.16
Antimony	µg/l	<26	<26	<26
Arsenic	µg/l	<1	<1	<1
Barium	µg/l	73	67	70
Bicarbonate	mg/l	246	49	148
Cadmium	µg/l	<2	2	<2
Calcium	mg/l	72.6	18.5	45.6
Carbon Dioxide	mg/l	3.9	2.5	3.2
Chloride	mg/l	12.4	0.6	6.5
Chromium	µg/l	<12	<12	<12
Color[2]		*	3-4	3-4
Copper	µg/l	5	3	4
Cyanide	mg/l	<0.01	<0.02	<0.02
Fluoride	mg/l	0.18	0.14	0.16
Hardness[3]	mg/l	261	60	160
Hydrogen Sulfide	mg/l	<0.01	<0.01	<0.01
Iron	µg/l	135	321	228
Lead	µg/l	<15	<15	<15
Magnesium	mg/l	19.2	3.3	11.2
Manganese	µg/l	47	138	92
Mercury	µg/l	<1	<1	<1
Nickel	µg/l	29	<18	<24
Nitrate (N)	mg/l	<0.1	2.2	<1.2
pH (Field)		*		
Phenols	µg/l	6	10	8
Phosphorus	mg/l	<0.03	<0.03	<0.03
Selenium	µg/l	0.3	0.2	0.2
Silver	µg/l	3	<3	<3
Sodium	mg/l	6.0	0.9	3.4
Strontium	µg/l	336	70	203
Sulfate	mg/l	36	13	24
Temperature	C°	21	21	21
Zinc	µg/l	6	15	10
Flow Rate	CFS	0.1495	5.295	2.723
Suspended Solids	mg/l	241	1980	1110
Dissolved Solids	mg/l	324	87	206

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[1] As calcium carbonate

[2] 0-500 color units

[3] Calcium and magnesium

* Not measured

Table 52. Analytical Results for Base-Flow and Runoff Water Samples (Grab, one sample each) from Small Weir at M09 (Unmined) Watershed Site.

Parameter	Units	Quantity	
		Baseflow	Runoff
Acidity	meq/l	0.11	0.08
Alkalinity[1]	mg/l	62	40
Aluminum	µg/l	616	219
Ammonia (N)	mg/l	0.02	0.05
Antimony	µg/l	<26	<26
Arsenic	µg/l	<1	<1
Barium	µg/l	42	27
Bicarbonate	mg/l	75	49
Cadmium	µg/l	<2	<2
Calcium	mg/l	33.8	20.3
Carbon Dioxide	mg/l	6.0	4.9
Chloride	mg/l	1.2	0.5
Chromium	µg/l	<12	13
Color[2]		*	1-2
Copper	µg/l	5	<2
Cyanide	mg/l	<0.01	<0.01
Fluoride	mg/l	0.19	0.12
Hardness[3]	mg/l	108	63
Hydrogen Sulfide	mg/l	<0.01	<0.01
Iron	µg/l	325	119
Lead	µg/l	<15	<15
Magnesium	mg/l	5.6	2.9
Manganese	µg/l	99	32
Mercury	µg/l	<1	<1
Nickel	µg/l	<18	<18
Nitrate (N)	mg/l	0.6	1.6
pH (Field)		*	*
Phenols	µg/l	11	11
Phosphorus	mg/l	0.12	<0.03
Selenium	µg/l	0.3	0.2
Silver	µg/l	<3	<3
Sodium	mg/l	3.2	1.3
Strontium	µg/l	127	72
Sulfate	mg/l	26	18
Temperature	C°	18	21
Zinc	µg/l	11	3
Flow Rate	CFS	<0.0021	0.193
Suspended Solids	mg/l	75	84
Dissolved Solids	mg/l	123	93

[1] As calcium carbonate

[2] 0-500 color units

[3] Calcium and magnesium

* Not measured

Table 53. Analytical Results for Base-Flow Water Samples (Grab, 3) from Large Flume at J11 (Unmined) Watershed Site.

Parameter	Units	Range		Average
Acidity	meq/l	0.03	0.14	0.09
Alkalinity[1]	mg/l	33	128	88
Aluminum	µg/l	<6	<9	<7
Ammonia (N)	mg/l	0.02	0.03	0.02
Antimony	µg/l	<13	<17	<15
Arsenic	µg/l	<1		<1
Barium	µg/l	22	28	25
Bicarbonate	mg/l	40	156	107
Cadmium	µg/l	<3	<6	<5
Calcium	mg/l	19.7	52.4	37.9
Carbon Dioxide	mg/l	2.6	62.6	25.9
Chloride	mg/l	5.6	13.8	10.5
Chromium	µg/l	<10		<10
Color[2]		0	500	200
Copper	µg/l	<1	2	<2
Cyanide	mg/l	<0.01		<0.01
Fluoride	mg/l	0.08	0.12	0.10
Hardness[3]	mg/l	62	190	135
Hydrogen Sulfide	mg/l	<0.01		<0.01
Iron	µg/l	<2	<5	<3
Lead	µg/l	<10	<15	<13
Magnesium	mg/l	3.2	14.4	9.7
Manganese	µg/l	7	57	25
Mercury	µg/l	<1	<2	<2
Nickel	µg/l	<6	<9	<7
Nitrate (N)	mg/l	0.1	1.8	0.9
pH (Field)		7.0	7.3	7.1
Phenols	µg/l	5	6	5
Phosphorus	mg/l	<0.03		<0.03
Selenium	µg/l	0.1	0.3	0.2
Silver	µg/l	<2	<3	<2
Sodium	mg/l	2.3	7.0	4.3
Strontium	µg/l	91	312	211
Sulfate	mg/l	23	64	47
Temperature	C°	0	5	2
Zinc	µg/l	<1	<5	<3
Flow Rate	CFS	0.0038	0.1081	0.042
Suspended Solids	mg/l	13	72	44
Dissolved Solids	mg/l	238	272	257

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[1] As calcium carbonate

[2] 0-500 color units

[3] Calcium and magnesium

Table 54. Analytical Results for Runoff Water Samples (Grab, 4) from Large Flume at J11 (Unmined) Watershed Site.

Parameter	Units	Range		Average
Acidity	meq/l	0.03	0.15	0.08
Alkalinity[1]	mg/l	17	84	35
Aluminum	µg/l	<6	12	<10
Ammonia (N)	mg/l	<0.01	0.08	<0.05
Antimony	µg/l	<10	<15	<11
Arsenic	µg/l	<1		<1
Barium	µg/l	25	37	31
Bicarbonate	mg/l	21	102	43
Cadmium	µg/l	<3	<6	<4
Calcium	mg/l	15.9	43.5	24.6
Carbon Dioxide	mg/l	4.2	20.8	10.9
Chloride	mg/l	6.6	11.0	9.5
Chromium	µg/l	<10		<10
Color[2]		100	500	400
Copper	µg/l	<1	3	<2
Cyanide	mg/l	<0.01	0.02	<0.02
Fluoride	mg/l	0.09	0.13	0.11
Hardness[3]	mg/l	55	148	84
Hydrogen Sulfide	mg/l	<0.01		<0.01
Iron	µg/l	10	19	14
Lead	µg/l	<12	<14	<13
Magnesium	mg/l	3.7	9.5	5.6
Manganese	µg/l	27	93	54
Mercury	µg/l	<2		<2
Nickel	µg/l	13	<18	<17
Nitrate (N)	mg/l	1.9	3.5	2.7
pH (Field)		6.5	7.5	7.2
Phenols	µg/l	4	7	6
Phosphorus	mg/l	<0.02	0.08	<0.05
Selenium	µg/l	0.2		0.2
Silver	µg/l	3	<4	<4
Sodium	mg/l	2.7	6.3	4.6
Strontium	µg/l	67	239	119
Sulfate	mg/l	23	53	34
Temperature	C°	3	7	5
Zinc	µg/l	3	<5	<4
Flow Rate	CFS	0.0200	1.76	0.89
Suspended Solids	mg/l	25	195	118
Dissolved Solids	mg/l	95	214	144

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[1] As calcium carbonate

[2] 0-500 color units

[3] Calcium and magnesium

Table 55. **Analytical Results for Base-Flow Water Sample (Grab, 1) from Small Weir at J11 (Unmined) Watershed Site.**

Parameter	Units	Quantity
Acidity	meq/l	0.07
Alkalinity[1]	mg/l	28
Aluminum	µg/l	25
Ammonia (N)	mg/l	0.17
Antimony	µg/l	<13
Arsenic	µg/l	<1
Barium	µg/l	14
Bicarbonate	mg/l	34
Cadmium	µg/l	<6
Calcium	mg/l	10.6
Carbon Dioxide	mg/l	3.5
Chloride	mg/l	0.5
Chromium	µg/l	<10
Color[2]		100
Copper	µg/l	4
Cyanide	mg/l	<0.01
Fluoride	mg/l	0.17
Hardness[3]	mg/l	38
Hydrogen Sulfide	mg/l	<0.01
Iron	µg/l	40
Lead	µg/l	<10
Magnesium	mg/l	2.7
Manganese	µg/l	3
Mercury	µg/l	<2
Nickel	µg/l	<6
Nitrate (N)	mg/l	1.1
pH (Field)		7.1
Phenols	µg/l	7
Phosphorus	mg/l	0.11
Selenium	µg/l	0.3
Silver	µg/l	<2
Sodium	mg/l	0.45
Strontium	µg/l	41
Sulfate	mg/l	14
Temperature	C°	3
Zinc	µg/l	13
Flow Rate	CFS	0.0141
Suspended Solids	mg/l	18
Dissolved Solids	mg/l	130

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[1] As calcium carbonate
[2] 0-500 color units
[3] Calcium and magnesium

Table 56. Analytical Results for Runoff Water Samples (Grab, 4) from Small Weir at J11 (Unmined) Watershed Site.

Parameter	Units	Range		Average
Acidity	meq/l	0.04	0.08	0.06
Alkalinity[1]	mg/l	8.6	17	13
Aluminum	µg/l	22	84	44
Ammonia (N)	mg/l	0.06	0.45	0.18
Antimony	µg/l	<10	<15	<11
Arsenic	µg/l	<1		<1
Barium	µg/l	9	26	14
Bicarbonate	mg/l	10	21	16
Cadmium	µg/l	<3	<6	<4
Calcium	mg/l	4.3	15.6	8.3
Carbon Dioxide	mg/l	4.7	53.1	18.4
Chloride	mg/l	1.5	7.1	3.1
Chromium	µg/l	<10	10	<10
Color[2]		500	1000	700
Copper	µg/l	4	6	5
Cyanide	mg/l	<0.01	0.01	<0.01
Fluoride	mg/l	0.11	0.14	0.12
Hardness[3]	mg/l	16	57	30
Hydrogen Sulfide	mg/l	<0.01		<0.01
Iron	µg/l	30	67	44
Lead	µg/l	<12	<14	<13
Magnesium	mg/l	1.2	4.3	2.3
Manganese	µg/l	7	27	13
Mercury	µg/l	<1	<2	<2
Nickel	µg/l	<9	<18	15
Nitrate (N)	mg/l	1.0	5.2	2.3
pH (Field)		6.4	7.7	7.1
Phenols	µg/l	7	11	8
Phosphorus	mg/l	0.10	0.32	0.22
Selenium	µg/l	0.2	0.4	0.3
Silver	µg/l	<3	<4	<4
Sodium	mg/l	0.24	0.74	0.40
Strontium	µg/l	19	58	32
Sulfate	mg/l	8	16	12
Temperature	C°	0	23	7
Zinc	µg/l	<1	<5	<3
Flow Rate	CFS	0.018	0.129	0.074
Suspended Solids	mg/l	8	2590	734
Dissolved Solids	mg/l	55	124	73

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[1] As calcium carbonate

[2] 0-500 color units

[3] Calcium and magnesium

Table 57. Analytical Results for Base-Flow Water Samples (3) from Weir at A06 (Unmined) Watershed Site.

Parameter	Units	Range		Average
Acidity	meq/l	0.06	0.35	0.17
Alkalinity[1]	mg/l	58	117	86
Aluminum	µg/l	<6	46	<22
Ammonia (N)	mg/l	<0.01	0.03	<0.02
Antimony	µg/l	<11	<27	<18
Arsenic	µg/l	<1	<2	<2
Barium	µg/l	35	57	43
Bicarbonate	mg/l	71	142	105
Cadmium	µg/l	<3	8	<6
Calcium	mg/l	27.2	50.7	38.7
Carbon Dioxide	mg/l	9.0	16.0	12.1
Chloride	mg/l	4.8	8.4	6.9
Chromium	µg/l	<10		<10
Color[2]		10	100	50
Copper	µg/l	2	7	4
Cyanide	mg/l	<0.01		<0.01
Fluoride	mg/l	0.10	0.22	0.17
Hardness[3]	mg/l	103	186	147
Hydrogen Sulfide	mg/l	<0.01		<0.01
Iron	µg/l	<5	50	<22
Lead	µg/l	<13	54	<27
Magnesium	mg/l	8.6	14.3	12.2
Manganese	µg/l	94	608	344
Mercury	µg/l	<1	<2	<2
Nickel	µg/l	<9	68	<35
Nitrate (N)	mg/l	<0.1	0.7	<0.3
pH (Field)		6.8		6.8
Phenols	µg/l	<4		<4
Phosphorus	mg/l	<0.02	<0.05	<0.03
Selenium	µg/l	0.2	0.4	0.3
Silver	µg/l	<3	9	<5
Sodium	mg/l	7.4	26.8	19.9
Strontium	µg/l	108	258	188
Sulfate	mg/l	58	69	65
Temperature	C°	0	7	3
Zinc	µg/l	<2	7	<5
Flow Rate	CFS	0.0065	0.0164	0.0098
Suspended Solids	mg/l	none	134	45
Dissolved Solids	mg/l	159	310	244

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[1] As calcium carbonate

[2] 0-500 color units

[3] Calcium and magnesium

Table 58. Analytical Results for Runoff Water Samples (10) from Weir at A06 (Unmined) Watershed Site.

Parameters	Units	Range		Average
Acidity	meq/l	0.03	0.16	0.08
Alkalinity[1]	mg/l	9.0	92	28
Aluminum	µg/l	<6	232	<41
Ammonia (N)	mg/l	<0.01	0.07	<0.02
Antimony	µg/l	<10	<26	<16
Arsenic	µg/l	<1	2	<2
Barium	µg/l	28	53	36
Bicarbonate	mg/l	11	112	35
Cadmium	µg/l	<2	<6	<3
Calcium	mg/l	12.1	28.0	16.2
Carbon Dioxide	mg/l	2.0	55.5	13.0
Chloride	mg/l	0.7	7.8	2.4
Chromium	µg/l	<10	<12	<10
Color[2]		1	1000	300
Copper	µg/l	<2	8	<3
Cyanide	mg/l	<0.01	0.01	<0.01
Fluoride	mg/l	0.07	0.20	0.10
Hardness[3]	mg/l	45	103	61
Hydrogen Sulfide	mg/l	<0.01		<0.01
Iron	µg/l	7	229	52
Lead	µg/l	<10	15	<14
Magnesium	mg/l	3.5	7.9	4.9
Manganese	µg/l	23	112	64
Mercury	µg/l	<1	<2	<2
Nickel	µg/l	<6	25	<14
Nitrate (N)	mg/l	<0.1	3.2	<1.4
pH (Field)		6.2	7.7	6.7
Phenols	µg/l	6	13	9
Phosphorus	mg/l	<0.01	0.22	<0.05
Selenium	µg/l	0.1	2.7	0.5
Silver	µg/l	<1	<4	<3
Sodium	mg/l	1.3	7.5	3.4
Strontium	µg/l	40	139	67
Sulfate	mg/l	28	41	33
Temperature	C°	1	18	9
Zinc	µg/l	3	30	<12
Flow Rate	CFS	0.260	1.92	0.84
Suspended Solids	mg/l	25	262	147
Dissolved Solids	mg/l	83	192	130

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[1] As calcium carbonate

[2] 0-500 color units

[3] Calcium and magnesium

Table 59. Analytical Results for Base-Flow Water Samples (5) From Weir at C06 (Unmined) Watershed Site (Analyzed by USGS)

Parameter	Units	Range		Average
Alkalinity	mg/l ($CaCO_3$)	35	49	42
Aluminum*	µg/l	100	21,000	7500
Ammonia	mg/l	0	0.17	0.05
Antimony*	µg/l	0	1	0.6
Arsenic*	µg/l	0	2	0.6
Barium*	µg/l	0	200	66
Bicarbonate	mg/l	18	60	40
Cadmium*	µg/l	0	1	0.3
Calcium	mg/l	11	23	17
Carbon dioxide	mg/l	24	27	25
Chloride	mg/l	2.4	3.3	2.8
Chromium*	µg/l	0	10	6.7
Color**		1	210	45
Copper*	µg/l	0	20	10
Cyanide	mg/l	0	0.01	0.005
Fluoride	mg/l			0.01
Hardness*	mg/l	41	92	69
Hydrogen sulfide	mg/l	0	0	
Iron	µg/l	40	140	88
Iron*	µg/l	280	34,000	7458
Lead*	µg/l	2	21	9
Magnesium	mg/l	4	8.5	6.3
Manganese	µg/l	80	210	140
Manganese*	µg/l	90	1100	354
Mercury*	µg/l			<0.5
Nickel*	µg/l	3	35	23
Nitrate	mg/l	0.04	0.40	0.22
pH (Field)		6.1	6.7	6.4
Phenols	µg/l	0	2	0.6
Phosphorus*	mg/l	0.01	0.56	0.2
Selenium*	µg/l	0	2	0.6
Silver*	µg/l	0	1	0.3
Sodium	mg/l	2.9	4.2	3.5
Sp. Conductance	µmhos	115	215	169
Strontium*	µg/l	50	150	100
Sulfate	mg/l	34	45	41
Temperature	C°	1	14	6
Zinc*	µg/l	20	110	53
Flow rate	CFS	0.03	0.21	0.11

* Unfiltered

** 0-500 color units

Table 60. Analytical Results for Runoff Water Samples (3) From Weir at C06 (Unmined) Watershed Site (Analyzed by USGS)

Parameter	Units	Range		Average
Alkalinity	mg/l ($CaCO_3$)	-	-	-
Aluminum*	μg/l	290	1600	733
Ammonia	mg/l	0.03	0.05	0.04
Antimony*	μg/l	0	2	1
Arsenic*	μg/l	1	3	1.7
Barium*	μg/l			100
Bicarbonate	mg/l	12	18	15.7
Cadmium*	μg/l	0	1	<1
Calcium	mg/l	11	13	12
Carbon dioxide		10.8	14.4	12.4
Chloride	mg/l	1.8	2.6	2.3
Chromium*	μg/l	0	10	6.7
Color**		21	24	23
Copper*	μg/l	0	10	6.7
Cyanide	mg/l			0
Flouride	mg/l	0.1	0.2	0.13
Hardness*	mg/l	43	50	46
Hydrogen sulfide	mg/l			0
Iron	μg/l	100	590	280
Iron*	μg/l	570	6100	3190
Lead*	μg/l	7	1	3.7
Magnesium	mg/l	3.5	4.8	4.0
Manganese	μg/l	30	100	70
Manganese*	μg/l	50	330	190
Mercury*	μg/l			<0.5
Nickel*	μg/l	4	31	15
Nitrate	mg/l	0.32	1.3	0.65
pH (Field)		6.2	6.4	6.3
Phenols	μg/l	0	1	<1
Phosphorus*	mg/l	0.06	0.16	0.1
Selenium*	μg/l	0	1	<1
Silver*	μg/l	0	2	1
Sodium	mg/l	2	2.3	2.2
Sp. Conductance	μmhos	95	118	107
Strontium*	μg/l	20	50	36
Sulfate	mg/l	34	36	35
Temperature	C°	5.0	8.5	6.7
Zinc*	μg/l	40	20	30
Flow rate	CFS	0.70	2.5	1.38
Suspended solids	mg/l	49	1080	408

* Unfiltered
** 0-500 color units

Table 61. Analytical Results for Base-Flow Water Samples (5) From Weir at A06 (Unmined) Watershed Site (Analyzed by USGS)

Parameter	Units	Range		Average
Alkalinity	mg/l ($CaCO_3$)	-	-	-
Aluminum*	µg/l	210	530	340
Ammonia	mg/l	0.01		<0.01
Antimony*	µg/l	0	2	1
Arsenic*	µg/l			0
Barium*	µg/l	0	100	33
Bicarbonate	mg/l	42	120	69
Cadmium*	µg/l			0
Calcium	mg/l	19	37	27
Carbon dioxide	mg/l	15.9	27.4	21.6
Chloride	mg/l	2.7	5.1	4.0
Chromium*	µg/l			<10
Color**		1	4	2
Copper*	µg/l	0	10	3
Cyanide	mg/l	0	0.01	<0.01
Fluoride	mg/l			0.1
Hardness*	mg/l	75	130	95
Hydrogen sulfide	mg/l			0
Iron	µg/l	50	140	104
Iron*	µg/l	200	980	500
Lead*	µg/l	1	4	2
Magnesium	mg/l	4.8	10	6.9
Manganese	µg/l	60	230	118
Manganese*	µg/l	80	230	124
Mercury*	µg/l			<0.5
Nickel*	µg/l	0	4	1.7
Nitrate	mg/l	0.01	0.69	0.5
pH (Field)		6.2	6.7	6.5
Phenols	µg/l	0	3	1
Phosphorus*	mg/l	0.02	0.04	0.03
Selenium*	µg/l	0	1	<1
Silver*	µg/l	0	1	<1
Sodium	mg/l	3.4	12	6.6
Sp. Conductance	µmhos	185	300	230
Strontium*	µg/l	70	160	100
Sulfate	mg/l	37	55	47
Temperature	C°	1	12	4.6
Zinc*	µg/l	10	30	20
Flow rate	CFS	0.01	0.13	0.07

* Unfiltered
** 0-500 color units

Table 62. Analytical Results for Runoff Water Samples (3) From Weir at A06 (Unmined) Watershed Site (Analyzed by USGS)

Parameter	Units	Range		Average
Alkalinity	mg/l ($CaCO_3$)	-	-	-
Aluminum*	μm/l	710	10,000	3970
Ammonia	mg/l	0.01	0.06	0.04
Antimony*	μg/l	0	2	1
Arsenic*	μg/l	0	5	<2
Barium*	μg/l	100	200	133
Bicarbonate	mg/l	15	21	17
Cadmium*	μg/l			0
Calcium	mg/l	9	15	12
Carbon dioxide	mg/l	12.0	16.8	14.1
Chloride	mg/l	2.2	2.7	2.4
Chromium*	μg/l	0	10	7
Color**		16	200	108
Copper*	μg/l	0	10	7
Cyanide	mg/l			0
Fluoride	mg/l	0.1	0.2	<0.2
Hardness*	mg/l	35	48	47
Hydrogen sulfide	mg/l			0
Iron	μg/l	80	270	173
Iron*	μg/l	1400	18,000	7000
Lead*	μg/l	3	20	13
Magnesium	mg/l	3	5	4.2
Manganese	μg/l	20	110	56
Manganese*	μg/l	70	810	323
Mercury*	μg/l			<0.5
Nickel*	μg/l	7	31	21
Nitrate	mg/l	0.58	1.6	1.1
pH (Field)				6.3
Phenols	μg/l	0	1	<1
Phosphorus*	mg/l	0.08	0.45	0.21
Selenium*	μg/l	0	1	<1
Silver*	μg/l	0	1	<1
Sodium	mg/l	1.1	3.1	2
Sp. Conductance	μmhos	130	176	150
Strontium*	μg/l	40	70	60
Sulfate	mg/l	27	39	34
Temperature	C°	3.5	5.0	4.2
Zinc*	μg/l	10	70	40
Flow rate	CFS	1.1	2.2	1.5
Suspended solids	mg/l	28	43	35

* Unfiltered

** 0-500 color units

Table 63. Concentration of Suspended Solids in Base-Flow and Runoff Water Samples from Different Watersheds.

Site	Watershed	Type of sample	No. events	Conc. range		Conc. avg.
				mg/l		mg/l
A06	Large	BF	3	0	134	45
A06	Large	RO	10	25	260	147
J11	Large	BF	3	13	72	44
J11	Large	RO	4	25	195	118
J11	Small	BF	1	18	18	18
J11	Small	RO	4	8	2590	734
C06	Large	BF	5	0	978	247
C06	Large	RO	4	97	1640	870
M09	Large	BF	5	0	415	157
M09	Large	RO	2	241	1980	1110
M09	Small	BF	1	75	75	75
M09	Small	RO	1	84	84	84

Table 64. Analytical Results for Precipitation Samples at M09 (Unmined) Watershed Site.

Parameter	Unit	Jan. 1977
Aluminum	µg/l	87
Antimony	µg/l	<11
Barium	µg/l	5
Bicarbonate	mg/l	None
Cadmium	µg/l	8
Calcium	mg/l	1.1
Copper	µg/l	29
Hydrogen Sulfide	mg/l	*
Iron	µg/l	68
Lead	µg/l	**
Magnesium	mg/l	0.13
Manganese	µg/l	20
Nickel	µg/l	30
Nitrate (N)	mg/l	<0.1
pH (Lab)		4.4
Phosphorus	mg/l	0.06
Silver	µg/l	4
Sodium	mg/l	0.56
Sp. Conductance	umhos/cm	27
Strontium	µg/l	5
Sulfate	mg/l	3
Zinc	µg/l	105

* Not measured

** Sample contamination from soldered stainless steel raingauge

Table 65. **Analytical Results for Precipitation Samples (9) at J11 (Unmined) Watershed Site.**

Parameter	Unit	Range		Average
Aluminum	µg/l	<6	1100	193
Antimony	µg/l	<9	<17	<14
Barium	µg/l	<2	6	<3
Bicarbonate	mg/l	none	4.2	0.6
Cadmium	µg/l	<3	11	<5
Calcium	mg/l	0.04	4.2	1.2
Copper	µg/l	<1	39	<12
Hydrogen Sulfide	mg/l	<0.01		<0.01
Iron	µg/l	<5	83	<35
Lead	µg/l	<12	38	<18
Magnesium	mg/l	0.01	0.73	0.23
Manganese	µg/l	<1	42	19
Nickel	µg/l	<7	<37	<15
Nitrate (N)	mg/l	0.4	3.0	1.2
pH (Lab)		4.0	5.6	4.4
Phosphorus	mg/l	<0.02	0.05	<0.03
Silver	µg/l	<2	<5	<3
Sodium	mg/l	0.06	0.81	0.21
Sp. Conductance	umhos/cm	26	87	44
Strontium	µg/l	<1	9	4
Sulfate	mg/l	<2	10	5
Zinc	µg/l	<5	150	<41

Table 66. Analytical Results for Sediment Fraction of Base-Flow Water Samples from Weir at C06 (Unmined) Watershed Site.

Parameter	Unit	Quantity*
Calcium	mg/g	2.97
Magnesium	mg/g	1.61
Aluminum	mg/g	5.64
Iron (total)	mg/g	13.2
Manganese	mg/g	1.23
Phosphorus (total)	mg/g	0.579
Cadmium	mg/g	0.001
Copper	mg/g	0.012
Lead	mg/g	0.019
Zinc	mg/g	0.058
Nickel	mg/g	0.027
Sodium	mg/g	0.066
Strontium	mg/g	0.013
Mercury	μg/g	0.073
Sulfate	mg/g	0.24
pH		6.6
TOC	mg/g	14.7

* Composite of 3 samples obtained on 5-16-76, 5-25-76 and 7-16-76.

Table 67. Analytical Results for Sediment Fraction of Runoff Water Samples (Grab) from Weir at C06 (Unmined) Watershed Site.

Parameter	Unit	Quantity*
Calcium	mg/g	2.37
Magnesium	mg/g	1.75
Aluminum	mg/g	6.86
Iron (total)	mg/g	13.8
Manganese	mg/g	0.757
Phosphorus (total)	mg/g	0.403
Cadmium	mg/g	0.003
Copper	mg/g	0.012
Lead	mg/g	0.020
Zinc	mg/g	0.054
Nickel	mg/g	0.015
Sodium	mg/g	0.058
Strontium	mg/g	0.011
Mercury	µg/g	0.063
Sulfate	mg/g	0.26
pH		6.4
TOC	mg/g	7.2

* Composite of 4 samples obtained on 7-8-76, 7-23-76, 7-24-76 and 8-15-76.

Table 68. Analytical Results for Sediment Fraction of Base-Flow Water Samples from Large Weir at M09 (Unmined) Watershed Site.

Parameter	Unit	Quantity*
Calcium	mg/g	10.7
Magnesium	mg/g	3.16
Aluminum	mg/g	9.32
Iron (total)	mg/g	14.8
Manganese	mg/g	1.19
Phosphorus (total)	mg/g	0.648
Cadmium	mg/g	0.002
Copper	mg/g	0.019
Lead	mg/g	0.028
Zinc	mg/g	0.067
Nickel	mg/g	0.036
Sodium	mg/g	0.096
Strontium	mg/g	0.049
Mercury	µg/g	I.S.
Sulfate	mg/g	0.32
pH		I.S.
TOC	mg/g	12.7

* Composite of 3 samples obtained on 5-24-76, 7-8-76 and 8-15-76.
I.S. = Insufficient sample

Table 69. Analytical Results for Sediment Fraction of Runoff Water Samples (Grab) from Large Weir at M09 (Unmined) Watershed Site.

Parameter	Unit	Quantity*
Calcium	mg/g	5.64
Magnesium	mg/g	2.12
Aluminum	mg/g	6.30
Iron (total)	mg/g	10.8
Manganese	mg/g	0.837
Phosphorus (total)	mg/g	0.332
Cadmium	mg/g	0.002
Copper	mg/g	0.013
Lead	mg/g	0.018
Zinc	mg/g	0.039
Nickel	mg/g	0.015
Sodium	mg/g	0.062
Strontium	mg/g	0.026
Mercury	µg/g	0.033
Sulfate	mg/g	0.23
pH		7.4
TOC	mg/g	10.7

* Composite of 2 samples obtained on 6-30-76 and 7-11-76.

Table 70. **Analytical Results for Sediment Fraction of Combined Base-Flow and Runoff Water Samples (Grab) from Small Weir at M09 (Unmined) Watershed Site.**

Parameter	Unit	Quantity*
Calcium	mg/g	6.39
Magnesium	mg/g	2.52
Aluminum	mg/g	10.2
Iron (total)	mg/g	16.1
Manganese	mg/g	0.907
Phosphorus (total)	mg/g	0.796
Cadmium	mg/g	0.002
Copper	mg/g	0.019
Lead	mg/g	0.026
Zinc	mg/g	0.080
Nickel	mg/g	0.054
Sodium	mg/g	0.070
Strontium	mg/g	0.031
Mercury	µg/g	I.S.
Sulfate	mg/g	0.28
pH		I.S.
TOC	mg/g	12.5

* Composite of baseflow sample obtained 6-30-76 and of runoff sample obtained

I.S. = Insufficient sample

Table 71. **Analytical Results for Sediment Fraction of Runoff Water Sample (Grab) from Small Weir at J11 (Unmined) Watershed Site.**

Parameter	Unit	Quantity*
Calcium	mg/g	2.40
Magnesium	mg/g	1.97
Aluminum	mg/g	6.80
Iron (total)	mg/g	11.4
Manganese	mg/g	0.597
Phosphorus (total)	mg/g	0.399
Cadmium	mg/g	<0.001
Copper	mg/g	0.013
Lead	mg/g	0.025
Zinc	mg/g	0.046
Nickel	mg/g	0.023
Sodium	mg/g	0.058
Strontium	mg/g	0.014
Mercury	µg/g	0.319**
Sulfate	mg/g	0.24
pH		6.6
TOC	mg/g	TBD

*For runoff event on 7-25-77. Mercury

**Mercury value obtained from composite of 2 subsequent events occuring on 5-12-77.

TBD = To be determined

Table 72. Analytical Results for Sediment Fraction of Runoff Water Samples from Weir at A06 (Unmined) Watershed Site.

Parameter	Unit	Quantity*
Calcium	mg/g	3.26
Magnesium	mg/g	2.52
Aluminum	mg/g	7.99
Iron (total)	mg/g	17.2
Manganese	mg/g	0.960
Phosphorus (total)	mg/g	0.648
Cadmium	mg/g	<0.001
Copper	mg/g	0.015
Lead	mg/g	0.022
Zinc	mg/g	0.094
Nickel	mg/g	0.018
Sodium	mg/g	0.082
Strontium	mg/g	0.017
Mercury	μg/g	I.S.
Sulfate	mg/g	I.S.
pH		I.S.
TOC	mg/g	14.4

* Composite of 4 samples obtained on 7-8-76, 2-24-76, 4-2-77 and 5-6-77.
I.S. = Insufficient sample

samples which were analyzed by OARDC, runoff and base-flow water samples (grab samples) from the main weirs on Watersheds A06 and M09 were collected during November 1975 through March 1976. These were shipped to the USGS Central Laboratory in Albany, New York for chemical analyses while the OARDC laboratory was being instrumented. The range and mean values for each parameter for the water samples analyzed by USGS are shown separately in Tables 59-62. Because these samples were treated differently than the others, their results were not included in the discussion.

Among the various parameters, the average concentrations of alkalinity, barium, calcium, chloride, magnesium, sodium, strontium, and total dissolved solids in base-flow water samples from Watershed C06 (Tables 47 and 48) were higher, and aluminum and suspended solids were lower compared with values obtained for runoff samples. The analyses of a base-flow water sample from the reservoir at Watershed C06 (Table 49) showed that the concentrations of all parameters with the exception of a few, such as dissolved solids, hardness, sulfate, etc., were considerably lower than those for base-flow samples obtained from Watershed C06 before reaching the reservoir.

The analyses of base-flow and runoff water samples from the large weir at Watershed M09 (Tables 50 and 51) revealed that there were some differences in the concentrations of various measured parameters. The average concentrations of aluminum, iron, manganese, and suspended solids in base flow were considerably lower than in runoff samples, while alkalinity, hardness, strontium, sulfate, and dissolved solids were higher. Similar results were obtained for base-flow and runoff water samples from the large flume (Tables 53 and 54) and the small weir (Tables 55 and 56) at J11 and also from Watershed A06 (Tables 57 and 58).

Since all chemical parameters are reported on the basis of concentration, flow rate becomes an important factor in water quality of unmined watersheds. This is evident when comparison is made between base-flow and runoff water from a given watershed. Generally base-flow water, as a result of reduced water volume, showed a higher dissolved solids content than the comparatively more dilute runoff water. The same can be said of the effect of flow rate on water composition within a series of samples of either type, whether base-flow or runoff. Thus, the dissolved solids content of both runoff and base-flow water tended to vary inversely with flow rate.

Runoff water, probably as a result of lower concentrations of major constituents, tended to show an increased solubility for certain, but not all, trace metals. Iron, aluminum, and manganese, where differences existed between base flow and runoff, tended to be elevated in runoff water. However, this was not uniformly the case, exceptions being elevated manganese in base-flow water from the small watershed at M09. Ammonia, nitrates, phosphates, and phenols, where differences existed, were more likely to be found in runoff water. As would be expected, suspended solids and color were higher in runoff water, but the differences between base flow and runoff with respect to these parameters varied widely.

While acidity showed a relatively wide range among all samples, average acidities for base-flow and runoff water samples from all sites were similar, with the exception of base-flow water from A06 and the large watershed at M09, where the average acidity was elevated 2 to 4 fold.

A number of parameters were consistently either too low to quantify or found only in ultratrace (less than 100 ppb) amounts in both base-flow and runoff water. These included arsenic, mercury, selenium, silver, cadmium, hexavalent chromium, phenols, copper, cyanide, lead, antimony, nickel, zinc, and hydrogen sulfide. Except for an occasional slightly higher value in the data, it may be said generally that arsenic, mercury, and selenium did not exceed 2 ppb; silver 5 ppb; cadmium, hexavalent chromium, phenols, cyanide, and hydrogen sulfide 10 ppb; copper 20 ppb; lead and antimony 50 ppb; nickel and zinc 100 ppb.

As an illustration of the preceding discussion of trends in the composition of base-flow and runoff waters, attention is drawn to Table 52 which compares single sample data for both base flow and runoff from Watershed M09. These data conformed generally, but not absolutely to the overall patterns of trends observed for water samples. Notable exceptions in this case were the relatively higher concentrations of iron, aluminum, and manganese in the base-flow water. It was apparent that the general pattern of water composition, being largely due to flow rate, was not universally applicable to all the data presented and hence did not constitute a paradigm in any strict sense.

Considering the average concentrations of different water quality parameters in water samples from four watersheds, it was quite evident that the concentration values of various parameters found in these samples were as low or lower than the recent U. S. Environmental Protection Agency recommended concentrations in drinking water (EPA, 1977). Suspended solids in runoff water samples was the only parameter that appeared to be higher in concentration at times (Table 63) than the desirable level for drinking water. The average concentrations of suspended solids in runoff water ranged from 118 to 1110 mg/l for the J11 and M09 large watersheds, respectively. In general, the average concentrations of suspended solids in runoff water samples were several fold higher than concentrations in their corresponding base-flow samples (Table 63).

Analyses of monthly composite precipitation samples from M09 and J11 (Tables 64 and 65) indicated that the concentration of several parameters in precipitation equaled or exceeded the concentrations of corresponding parameters in runoff water. However, the precipitation data for M09 were marred by the facts that: 1. only one monthly composite sample was collected prior to mining, and 2. during the first seven months, precipitation was collected in a soldered stainless steel raingauge and showed, by comparison with subsequent analyses on precipitation collected in a plastic raingauge, slight, but significant, elevations in the concentrations of copper, zinc, and manganese and a dramatic increase in lead. The lead concentration of the precipitation collected in the soldered stainless steel raingauge increased to a maximum value of 0.8 ppm in February, 1977, compared with an average of less than 15 ppb lead in later samples from plastic raingauges. Accordingly, in the case of M09, the contribution to runoff water quality from precipitation was based on the seven-month period from August, 1977, through February, 1978, during which time precipitation was collected exclusively in plastic. While it is possible to imagine that precipitation during this period in the vicinity of disturbed land could be modified by entrapment of airborne particles, comparison with precipitation from J11 showed no differences with respect to the parameters under consideration.

Presented are the concentrations of different chemical constituents of the sediment fraction for base flow and runoff from unmined C06 and M09 in Tables 66-70, and runoff from J11 and A06 in Tables 71 and 72.

Since the reported results for a given watershed were based on the sediment chemical analyses of a single sample (composite of several events), no range or average concentrations for any of the measured parameters could be obtained. Although the changes in the concentrations of a given parameter with respect to time could not be determined due to the confounding effect of sediment sampling, the concentrations of the measured parameters from base flow and runoff could be compared. With the exception of total organic carbon (TOC), the concentrations of various parameters in the sediment fraction for base flow were nearly the same as for runoff water samples obtained from the C06 watershed site. However, for the M09 site, the concentrations of all constituents in the base-flow sediment fraction were considerably higher than in runoff sediment with the exception of the cadmium concentrations which were the same in runoff and base-flow sediment samples. Irrespective of the watershed sites, the order of concentrations of the major constituents in the sediment was iron $\geq$ TOC > aluminum > calcium > magnesium > manganese.

V. GROUND-WATER HYDROLOGY

A. Experimental Procedures

Descriptions of the geology and ground-water conditions are based mainly on subsurface data. Data collection for Watershed C06, M09, J11, J08, and A06 are summarized in Figure 58-62 and described below. The last premining data at C06 were collected in November, 1976 and at M09 in December, 1976. Data from the unmined watersheds (J11, J08, and A06) were collected before March, 1978.

Continuous coring provided stratigraphic definition of each watershed. A single core was obtained near the divide of each watershed, except at C06, where cores from three locations were used to construct the stratigraphic column (Figures 16-20).

Observation well networks were established in each watershed. The wells were drilled by the air-rotary method and each was cased so as to be open to only one of three major saturated zones. Most wells were completed in or fully penetrate one of the top two zones. At J08, only one well was constructed in each zone. Four wells were redrilled, and slotted casing was installed because of caving. Well W157, a dug well in the upper part of the middle aquifer at A06, is a Science and Education Administration (U. S. Department of Agriculture) well. The "dug" well at M09 is an unused domestic well in the upper part of the middle aquifer. At C06, M09, and A06, elevations were determined at each observation well from nearby bench marks, and those at J11 were determined from an assumed elevation based on the U. S. Geological Survey topographic map. Elevations of wells were not determined at J08. Data pertaining to the wells are listed in Table 73. At the mined sites, all wells were destroyed by mining except W10-3 at C06, and W5-2 and W10-3 at M09.

Gamma and electric logs were collected from most wells and core holes, and caliper and neutron logs were collected from selected wells.

Water levels were measured monthly in all wells and recorded hourly using digital recorders in selected wells.

Aquifer tests (pumping and slug tests) were made at M09 and A06 to determine hydrologic properties. Mining took place before any tests were made at C06, and many of the wells at M09 were destroyed before testing began. Pumping rates (about half of a gallon per minute) and duration of pumping (1 to 2 hours) were limited by the very low water-yielding capability of the rocks. In many wells the available head was too low to warrant test pumping. Data were analyzed according to the methods of Boulton (1963), Theis et al, (1963), and computer simulation (Trescott et al, 1976) by modeling the pumping well as the central node of a two-dimensional grid. Slug tests were made at some of

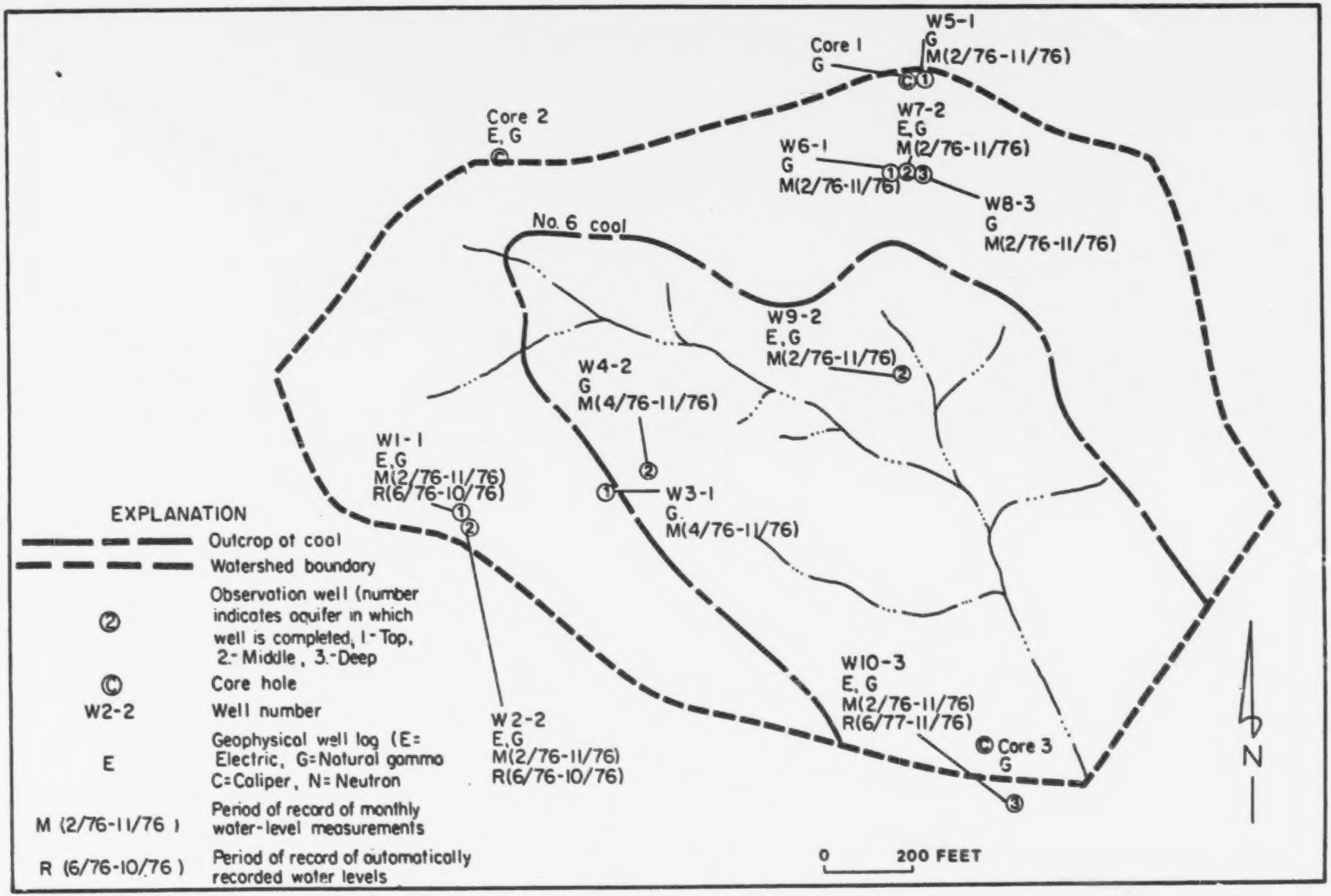

W5-1
G
M(2/76-11/76)
Core 1
G
Core 2
E, G
W7-2
E,G
M(2/76-11/76)
W6-1
G
M(2/76-11/76)
W8-3
G
M(2/76-11/76)
No. 6 coal
W9-2
E,G
M(2/76-11/76)
W4-2
G
M(4/76-11/76)
W1-1
E,G
M(2/76-11/76)
R(6/76-10/76)
W3-1
G.
M(4/76-11/76)
W10-3
E, G
M(2/76-11/76)
R(6/77-11/76)
Core 3
G
W2-2
E,G
M(2/76-11/76)
R(6/76-10/76)
N
0
200 FEET
EXPLANATION
Outcrop of coal
Watershed boundary
②
Observation well (number indicates aquifer in which well is completed, 1- Top, 2- Middle, 3- Deep
Ⓒ
Core hole
W2-2
Well number
E
Geophysical well log (E= Electric, G= Natural gamma C= Caliper, N= Neutron
M (2/76-11/76)
Period of record of monthly water-level measurements
R (6/76-10/76)
Period of record of automatically recorded water levels

Figure 58. Locations of and Data Obtained from Observation Wells and Core Holes at C06

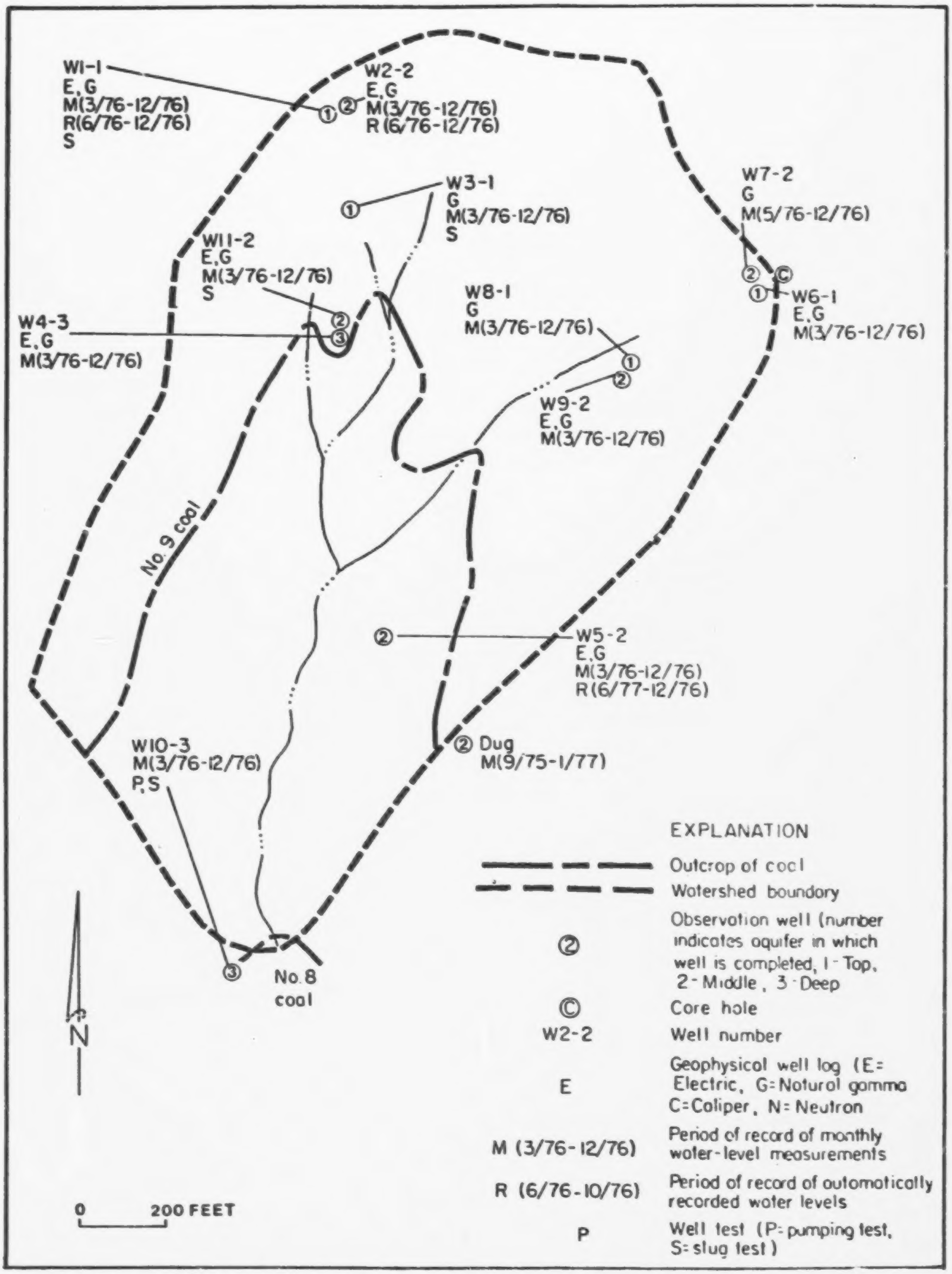

W1-1
E, G
M(3/76-12/76)
R(6/76-12/76)
S
W2-2
E, G
M(3/76-12/76)
R(6/76-12/76)
W3-1
G
M(3/76-12/76)
S
W7-2
G
M(5/76-12/76)
W11-2
E, G
M(3/76-12/76)
S
W4-3
E, G
M(3/76-12/76)
W8-1
G
M(3/76-12/76)
W6-1
E, G
M(3/76-12/76)
W9-2
E, G
M(3/76-12/76)
No. 9 coal
W5-2
E, G
M(3/76-12/76)
R(6/77-12/76)
Dug
M(9/75-1/77)
W10-3
M(3/76-12/76)
P, S
No. 8
coal
N
0
200 FEET
EXPLANATION
Outcrop of coal
Watershed boundary
②
Observation well (number indicates aquifer in which well is completed, 1 - Top, 2 - Middle, 3 - Deep
©
Core hole
W2-2
Well number
E
Geophysical well log (E= Electric, G= Natural gamma C= Caliper, N= Neutron
M (3/76-12/76)
Period of record of monthly water-level measurements
R (6/76-10/76)
Period of record of automatically recorded water levels
P
Well test (P= pumping test, S= slug test)

Figure 59. Locations of and Data Obtained from Observation Wells and Core Holes at M09

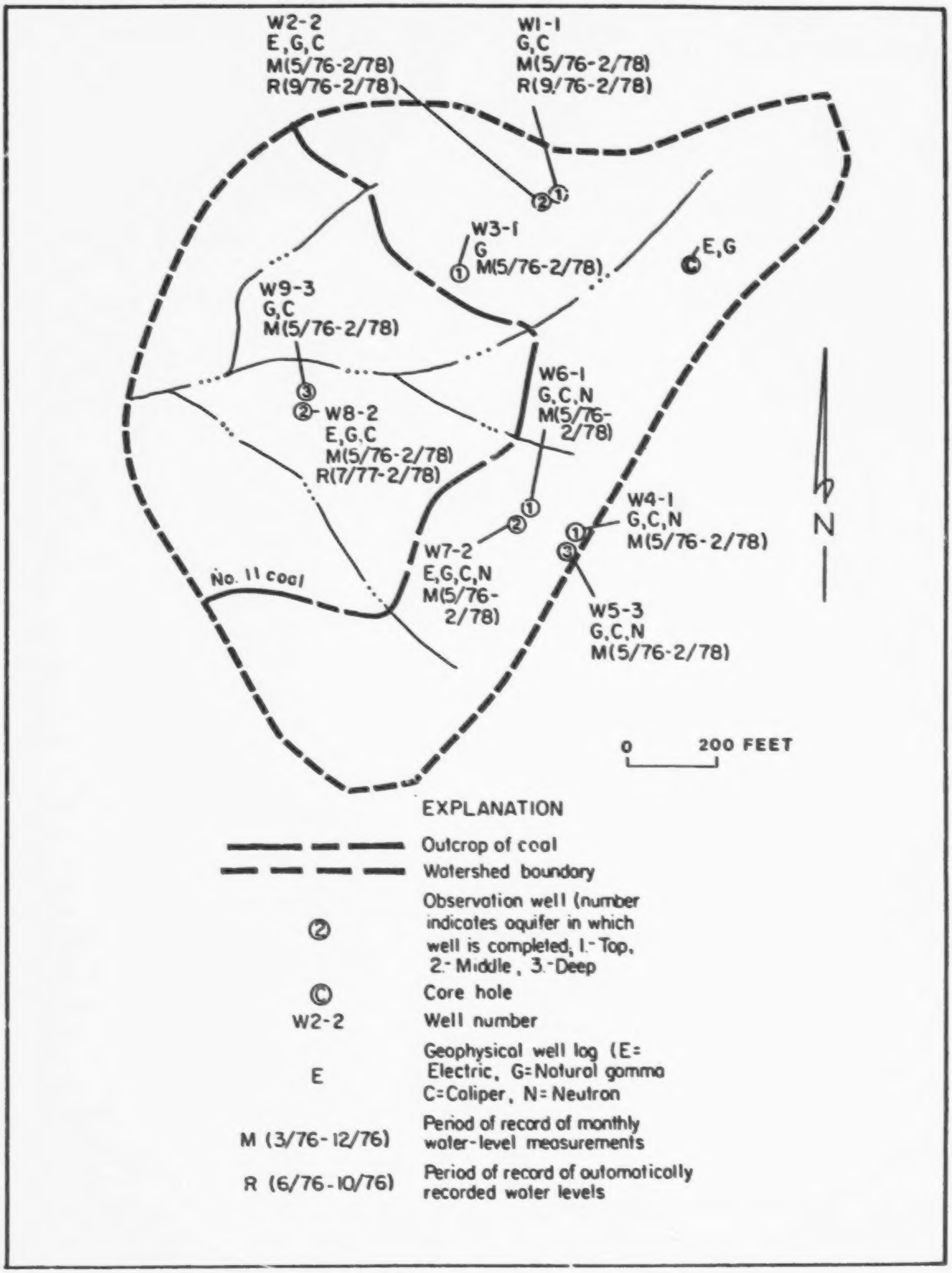

W2-2
E,G,C
M(5/76-2/78)
R(9/76-2/78)
W1-1
G,C
M(5/76-2/78)
R(9/76-2/78)
W3-1
G
M(5/76-2/78)
E,G
W9-3
G,C
M(5/76-2/78)
W6-1
G,C,N
M(5/76-2/78)
W8-2
E,G,C
M(5/76-2/78)
R(7/77-2/78)
W4-1
G,C,N
M(5/76-2/78)
W7-2
E,G,C,N
M(5/76-2/78)
W5-3
G,C,N
M(5/76-2/78)
No. 11 coal
N
0
200 FEET
EXPLANATION
Outcrop of coal
Watershed boundary
Observation well (number indicates aquifer in which well is completed; 1.-Top, 2.-Middle, 3.-Deep
Core hole
W2-2
Well number
E
Geophysical well log (E= Electric, G=Natural gamma C=Caliper, N=Neutron
M (3/76-12/76)
Period of record of monthly water-level measurements
R (6/76-10/76)
Period of record of automatically recorded water levels

Figure 60. Locations of and Data Obtained from Observation Wells and Core Holes at J11

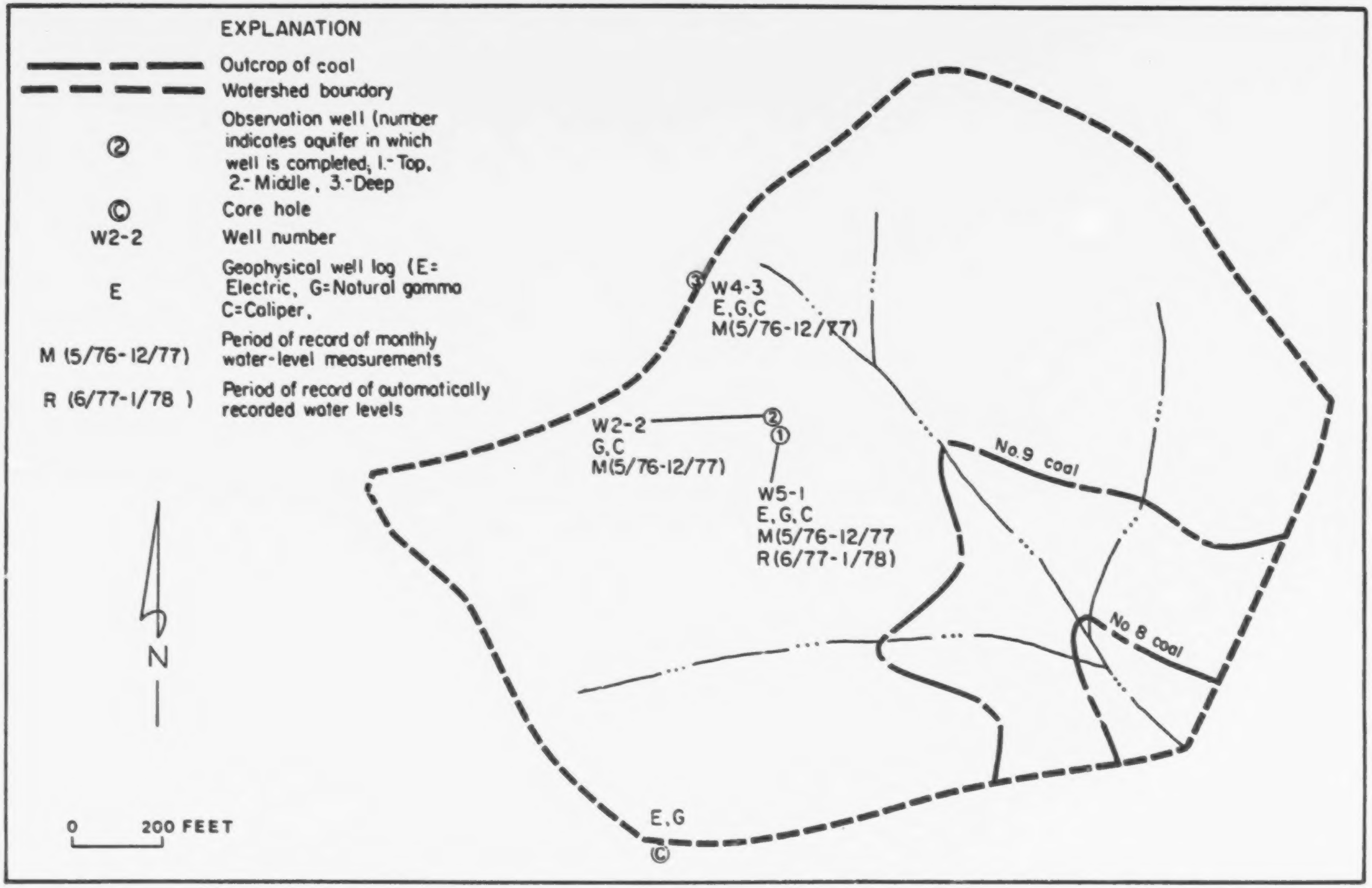

EXPLANATION
Outcrop of coal
Watershed boundary
② Observation well (number indicates aquifer in which well is completed; 1.- Top, 2.- Middle, 3.- Deep
© Core hole
W2-2 Well number
E Geophysical well log (E= Electric, G=Natural gamma C=Caliper,
M (5/76-12/77) Period of record of monthly water-level measurements
R (6/77-1/78) Period of record of automatically recorded water levels
W4-3
E,G,C
M(5/76-12/77)
W2-2
G,C
M(5/76-12/77)
W5-1
E,G,C
M(5/76-12/77
R(6/77-1/78)
No.9 coal
No 8 coal
E,G
N
0
200 FEET

Figure 61. Locations of and Data Obtained from Observation Wells and Core Holes at J08

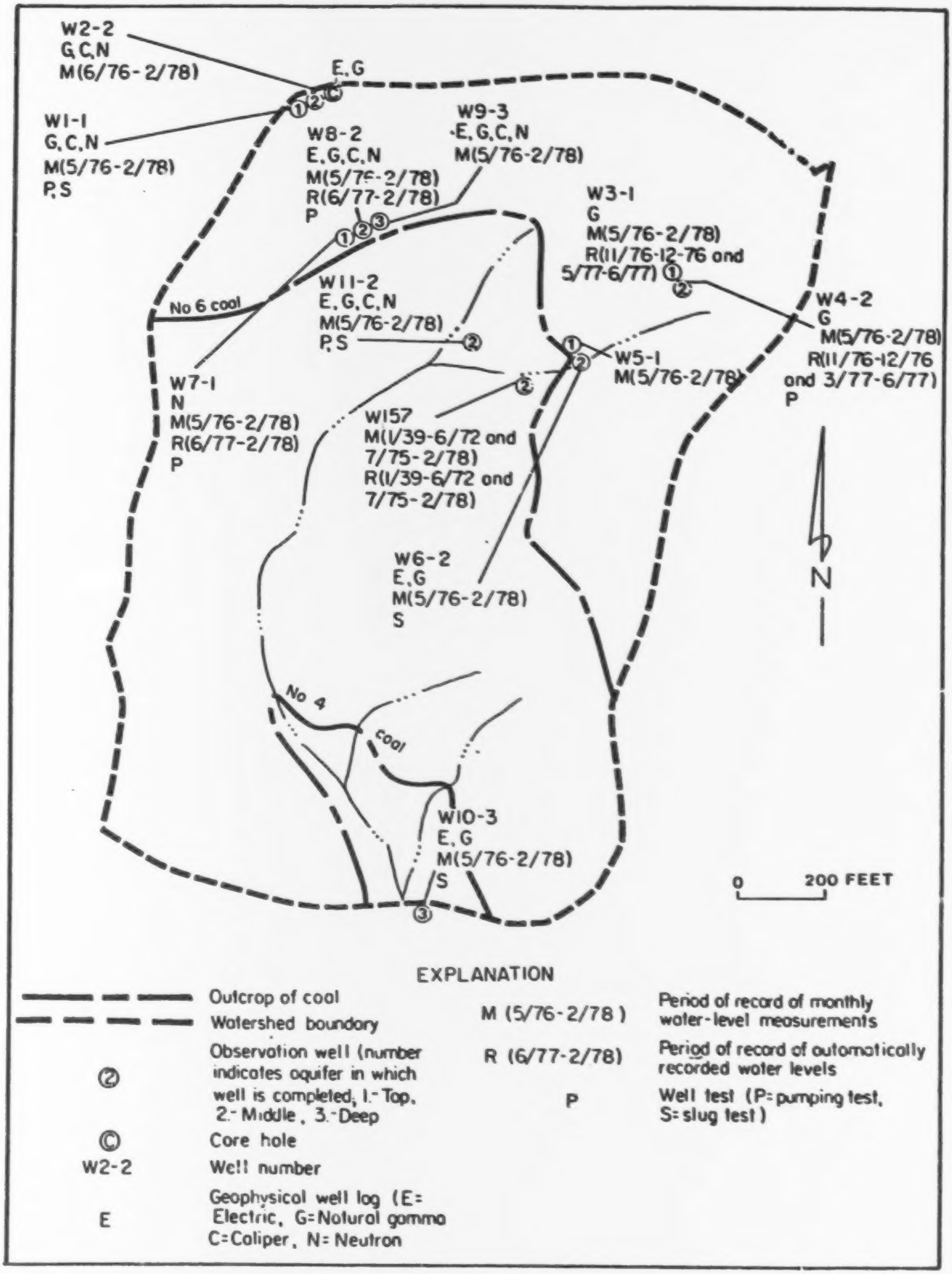

W2-2
G,C,N
M(6/76-2/78)
E,G
W1-1
G,C,N
M(5/76-2/78)
P,S
W8-2
E,G,C,N
M(5/76-2/78)
R(6/77-2/78)
P
W9-3
E,G,C,N
M(5/76-2/78)
W3-1
G
M(5/76-2/78)
R(11/76-12-76 and
5/77-6/77)
W4-2
G
M(5/76-2/78)
R(11/76-12/76
and 3/77-6/77)
P
No 6 coal
W11-2
E,G,C,N
M(5/76-2/78)
P,S
W5-1
M(5/76-2/78)
W7-1
N
M(5/76-2/78)
R(6/77-2/78)
P
W157
M(1/39-6/72 and
7/75-2/78)
R(1/39-6/72 and
7/75-2/78)
W6-2
E,G
M(5/76-2/78)
S
N
No 4
coal
W10-3
E,G
M(5/76-2/78)
S
0
200 FEET
EXPLANATION
Outcrop of coal
Watershed boundary
②
Observation well (number indicates aquifer in which well is completed, 1.- Top, 2.- Middle, 3.- Deep
©
Core hole
W2-2
Well number
E
Geophysical well log (E= Electric, G= Natural gamma C= Caliper, N= Neutron
M (5/76-2/78)
Period of record of monthly water-level measurements
R (6/77-2/78)
Period of record of automatically recorded water levels
P
Well test (P= pumping test, S= slug test)

Figure 62. Locations of and Data Obtained from Observation Wells and Core Holes at A06

Table 73. Data Pertaining to Observation Wells

Watershed	Well	Land surface elevation, in feet above mean sea level	Total depth, in feet	Casing depth, in feet	Approximate depth to water, in feet (July 1976 except as indicated)
C06	W1-1	1051.46	132	22	84
	W2-2	1051.59	245	140	186
	W3-1	945.54	29	20	20
	W4-2	914.28	100	100(slotted)	50(Oct 1976)
	W5-1	1019.18	109	24	100
	W6-1	952.70	41	21	36
	W7-2	952.42	140	50	93
	W8-3	953.69	200	147	193
	W9-2	877.82	60	19	25
	W10-3	820.47	62	19	12
N09	W1-1	1097.83	90	19	62
	W2-2	1097.97	181	95	91
	W3-1	1039.93	31	12	15
	W4-3	1020.57	260	102	234
	W5-2	973.03	49	17	21
	W6-1	1123.07	130	20	50
	W7-2	1122.90	213	134	186
	W8-1	1053.59	55	21	48
	W9-2	1053.69	140	58	67
	W10-3	941.51	190	190(slotted)	36(Oct 1976)
	W11-2	1020.65	100	20	14
	Dug	1001.97	20	--	11
J11	W1-1	1259.50	62	18	54
	W2-2	1259.41	211	65	85
	W3-1	1235.20	38	19	35
	W4-1	1251.37	60	19	53
	W5-3	1251.74	280	218	Dry
	W6-1	1238.36	46	18	39
	W7-2	1237.25	192	54	65
	W8-2	1156.67	105	20	36
	W9-3	1154.60	198	120	Dry
J08	W2-2	--	220	138	132
	W4-3	--	360	232	273
	W5-1	--	125	20	59
A06	W1-1	1207.84	90	19	84
	W2-2	1207.29	169	99	157
	W3-1	1206.26	75	18	67
	W4-2	1206.07	170	* 170(slotted)	93(Nov 1976)
	W5-1	1136.82	10	9	Dry
	W6-2	1136.32	98	19	27
	W7-1	1138.28	12	10	5
	W8-2	1138.64	101	19	30
	W9-3	1138.35	183	* 183(slotted)	111(Nov 1976)
	W10-3	1011.87	66	17	11
	W11-2	1092.35	56	18	16
	W157**	1115.45	14	--	9

* Casing diameter is 4 inches; casing diameter in other wells is 6 inches.

** Dug well.

the wells by injecting 8 to 10 gallons of water and measuring the rate of decline of the water level. Slug-test data were analyzed by the method of Cooper et al, (1967).

B. Results and Discussion

Ground water is stored and transmitted within open spaces in the rock. The openings are primary (intergranular pore space) or secondary (fractures and bedding-plane openings). Within the top 250 feet in each watershed, poorly permeable clay or shale beds that underlaid the coal seams were sufficiently continuous to form bases for two major perched saturated zones. The occurrence of these zones is illustrated for C06 (Figure 63) as an example. The major saturated zones are referred to herein as "aquifers" for convenience, even though they yielded only small quantities of water to wells (typically less than 1 gallon per minute).

The ground-water systems of the study watersheds were similar (Figure 63). The top aquifer at each site received recharge from precipitation. Surface discharge occurred along the edge of the aquifer (outcrop of the top coal) as spring flow or evapotranspiration. Subsurface discharge was by leakage through the underclay that formed the base of the aquifer and, in places, as underflow across watershed boundaries.

The middle aquifer was recharged by leakage through the overlying clay confining bed and by precipitation where the clay bed was absent. Top-aquifer spring flow probably provided recharge also. Lateral movement in the middle aquifer was generally toward the stream draining the watershed. Discharge from the middle aquifer occurred as base flow, evapotranspiration near the stream, leakage downward through the underclay, and in some places as underflow. Deeper ground water was part of the regional flow system.

Aquifer-test results are given in (Table 74). Although aquifer heterogeneity caused some variation in results from different wells in the same aquifer, results depended also on the method of analysis. The short pumping tests were hard to analyze by the type-curve method, and results of the slug tests are questionable when that method is applied to unconfined aquifers. Hydraulic conductivity values determined by computer simulation were in agreement with those from the type-curve analyses. Values of specific yield calculated from type-curve analyses (Table 74) seem high for this type of aquifer; computer simulation produces more realistic values.

Analyses of pumping tests did not take into account storage changes in the well. Re-analyses of wells W5-2 at M09 and W8-2 at A06 suggested that, when this factor is considered, determined hydraulic conductivity values were in the same order of magnitude as those shown in Table 74.

The potentiometric surface in each aquifer fluctuated naturally in response to changing rates of aquifer recharge and discharge. Water

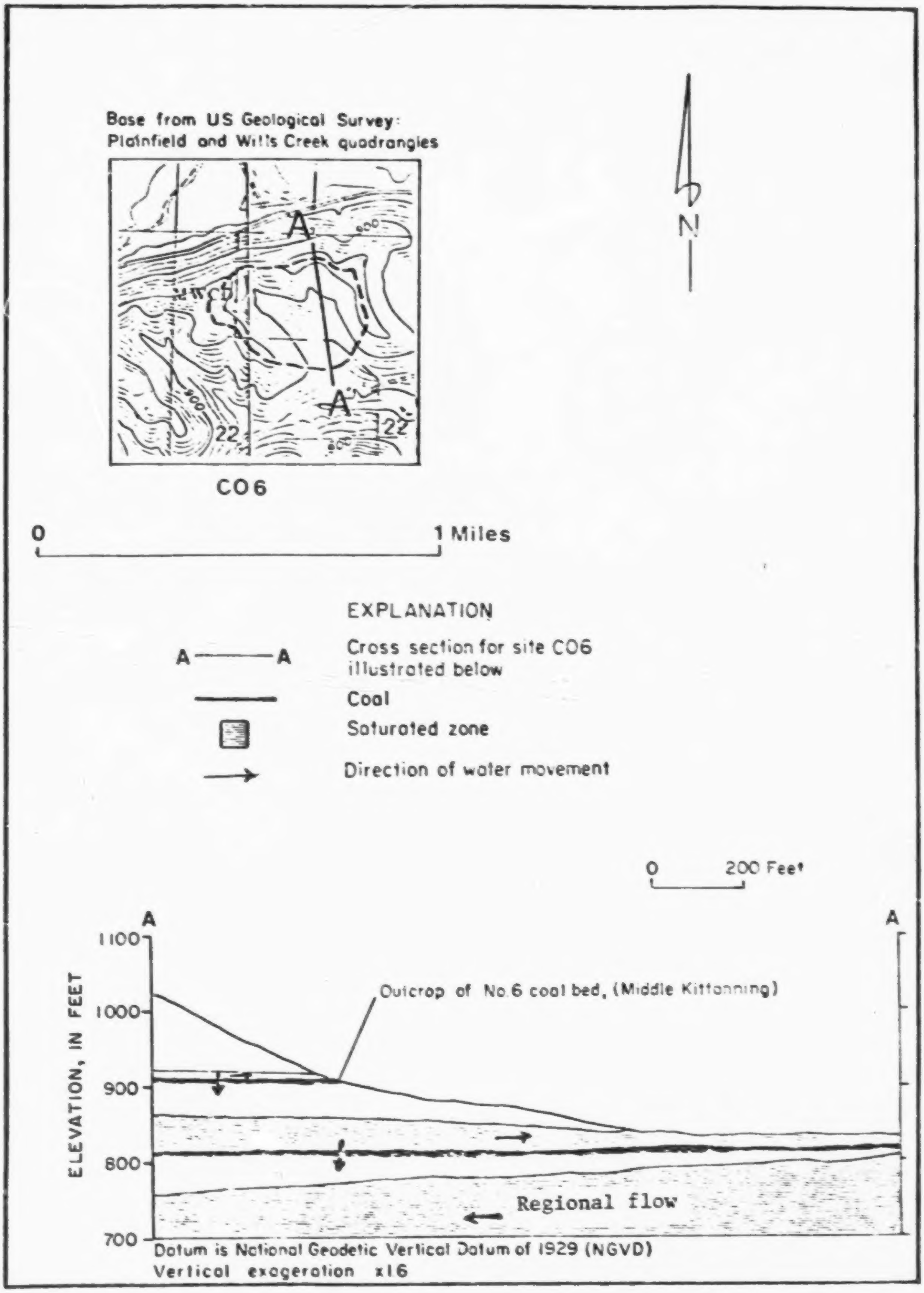

Base from US Geological Survey:
Plainfield and Wills Creek quadrangles
A
A
800
22
22
CO6
0
1 Miles
N
EXPLANATION
A——A
Cross section for site CO6 illustrated below
Coal
Saturated zone
Direction of water movement
0
200 Feet
A
A
1100
1000
900
800
700
ELEVATION, IN FEET
Outcrop of No.6 coal bed, (Middle Kittanning)
Regional flow
Datum is National Geodetic Vertical Datum of 1929 (NGVD)
Vertical exageration x16

Figure 63. Geologic Section for C06 Illustrating Occurrence of Major Saturated Zones

Table 74. Results of Aquifer Tests (Unmined Conditions)

Watershed	Well	Hydraulic conductivity (x 10^{-7} ft/s)				Specific yield	
		Pumping test (type curve)	Pumping test (computer simulation)	Pumping test (based on specific capacity)	Slug test	Type curve	Computer simulation
M09	W1-1	--	--	--	110	--	--
	W3-1	--	--	--	220	--	--
	W5-2	3.1	1.0	140	--	0.25	0.12
	W10-3	--	--	--	3.6	--	--
	W11-2	--	--	--	6.2	--	--
A06	W1-1	1.8	1.0	10	1.8	.28	.12
	W4-2	.81	--	5.8	--	.26	--
	W6-2	--	--	--	3.2	--	--
	W8-2	.58	.80	5.2	--	.43	.17
	W10-3	--	--	--	0.81	--	--
	W11-2	3.0	--	38	14	.47	--

levels in the top two aquifers fluctuated annually over several feet. Daily fluctuations were on the order of a few tenths of a foot. Recharge resulted from previous rainfall or snowmelt events with water taking some time to percolate through the unsaturated zone, depending on the zone's thickness and hydraulic conductivity. Discharge variations resulted from head changes caused by recharge and by diurnal and seasonal evapotranspiration variations. Water levels in deep aquifers (below the top two) typically fluctuated slowly over an annual range usually of less than 2 feet.

Water-level declines in some wells at C06 and M09 during the last few months of 1976 were probably in response to strip mining of adjacent watersheds.

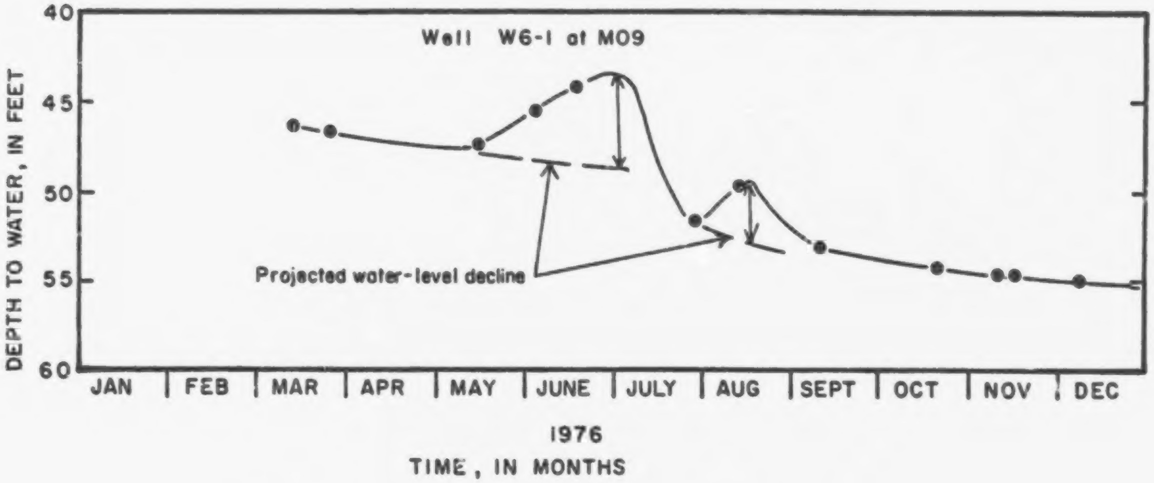
Ground-water recharge was estimated from hydrographs (example in Figure 64) of observation wells in the top aquifers and parts of the middle aquifers not overlain by the top underclay. This method involves an assumption that most recharge occurs during water level rises. Results for part of 1976 and 1977 (Table 75) showed a wide range. Precipitation differences were not great enough to account for the wide range; it may have been due to areal variation of specific yield (a uniform value of 0.12 for specific yield was assumed in the calculations).

Ground-water systems of individual study sites are described below.

1. Watershed C06

Topography and water-table elevations within the watershed suggested that the ground-water divides for both the top and middle aquifers at C06 coincided with the surface drainage divide. The top aquifer (Figure 65) was above the clay that underlies the Middle Kittanning No. 6 coal bed. The middle aquifer (Figure 66) was above the clay that underlies the Brookville No. 4 coal bed. Water in the deep aquifer moved northward; the top of this saturated zone was 30 to 100 feet below the middle aquifer.

Data for components of the hydrologic system at C06 are shown in Figure 67. The seasonal relationship between precipitation and groundwater levels was exemplified by the June, 1976 rises in wells W1-1 and W2-2 in response to May and June precipitation (the level in W2-2 probably rose partly because of increased leakage from the top aquifer). Daily records for July and August illustrated poor correlation between individual rains and ground-water levels. Surface discharge from the top aquifer occurred along the coal outcrop as evapotranspiration and spring flow. Flow was gaged at one spring site (Figures 65 and 67), and not gaged at another spring of similar flow and at several smaller springs and seepage areas. The gaged spring flow, therefore, represented a minimum value of surface discharge from the top aquifer. Rates of evapotranspiration and other spring flows were undetermined but probably made the total discharge rate much greater. Surface discharge from the middle aquifer



Recharge = (sum of water-level rises) x (assumed specific yield)
= (4.6 + 2.7) feet x (.12)
= 0.90 feet of water

Figure 64. Observation-Well Hydrograph Illustrating Method of Calculating Ground-Water Recharge

Table 75. Recharge from Precipitation as Calculated from Observation-Well Hydrographs.

Watershed	Median value of calculated recharge, in feet of water	
	1976*	1977
C06	0.2 (6 wells)	--- (mined)
M09	.4 (5 wells)	--- (mined)
J11	.7 (5 wells)	1.8 (5 wells)
J08	.1 (1 well)	.1 (1 well)
A06	.4 (5 wells)	1.7 (5 wells)

*Partial value based on incomplete data (February-October at C06 and M09; May-December at J11, J08, and A06).

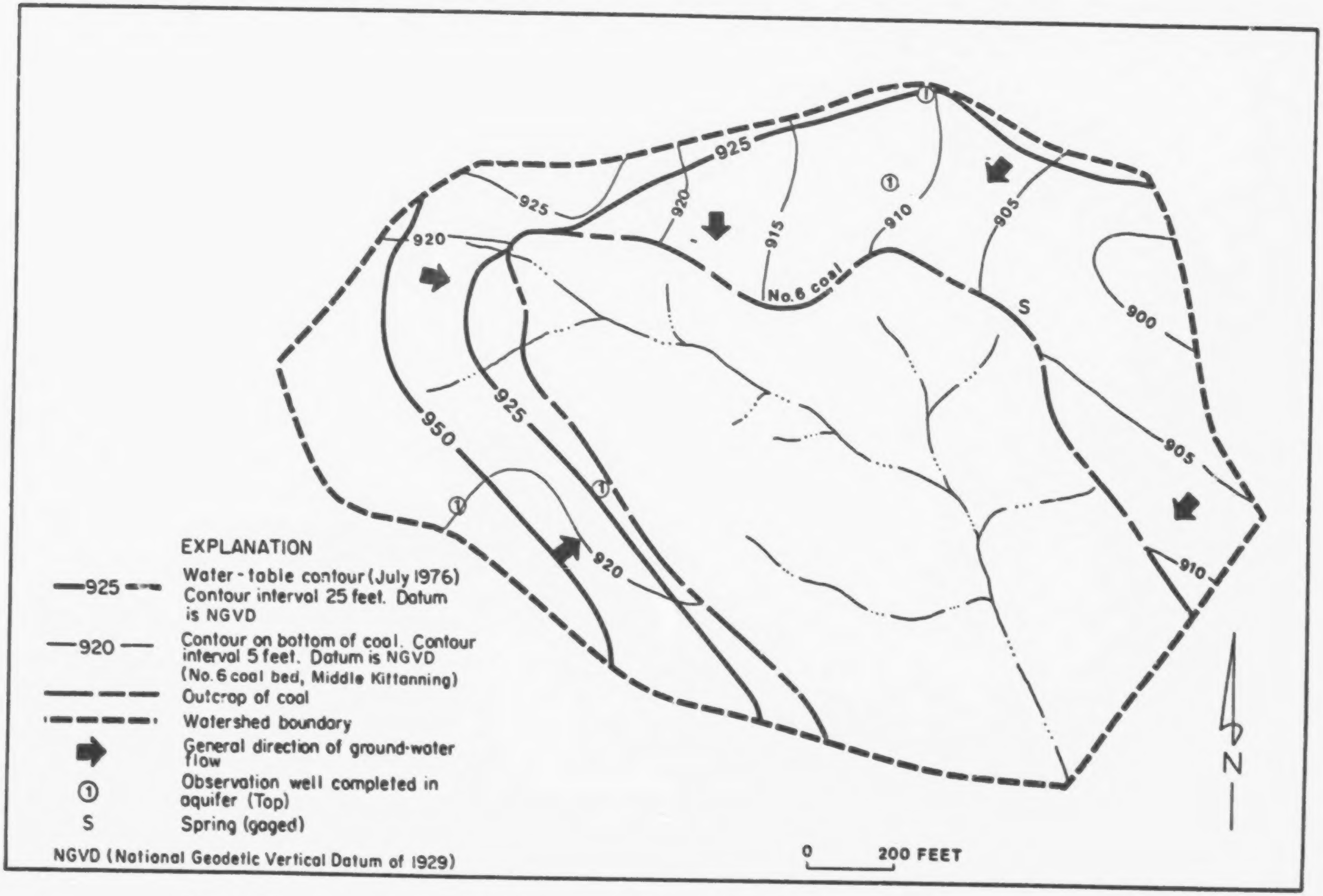

925
925
920
920
925
915
910
905
900
No.6 coal
S
950
925
920
905
910
EXPLANATION
925 Water-table contour (July 1976) Contour interval 25 feet. Datum is NGVD
920 Contour on bottom of coal. Contour interval 5 feet. Datum is NGVD (No. 6 coal bed, Middle Kittanning)
Outcrop of coal
Watershed boundary
General direction of ground-water flow
① Observation well completed in aquifer (Top)
S Spring (gaged)
NGVD (National Geodetic Vertical Datum of 1929)
0 200 FEET
N

Figure 65. Potentiometric Surface and Base of Top Aquifer at C06

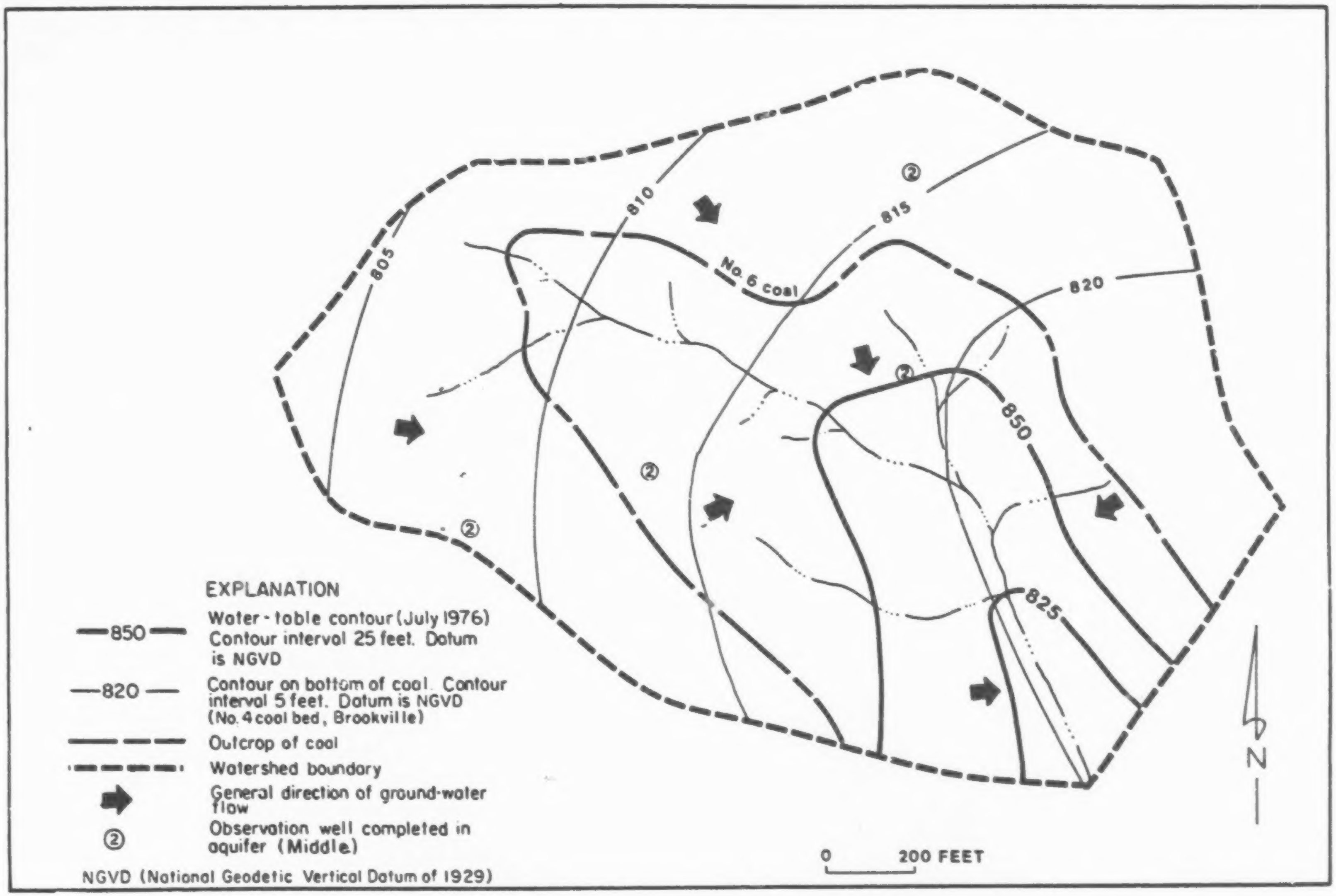

805
810
815
820
No. 6 coal
850
825
②
EXPLANATION
—850— Water-table contour (July 1976) Contour interval 25 feet. Datum is NGVD
—820— Contour on bottom of coal. Contour interval 5 feet. Datum is NGVD (No. 4 coal bed, Brookville)
Outcrop of coal
Watershed boundary
General direction of ground-water flow
② Observation well completed in aquifer (Middle)
NGVD (National Geodetic Vertical Datum of 1929)
0
200 FEET
N

Figure 66. Potentiometric Surface and Base of Middle Aquifer at C06

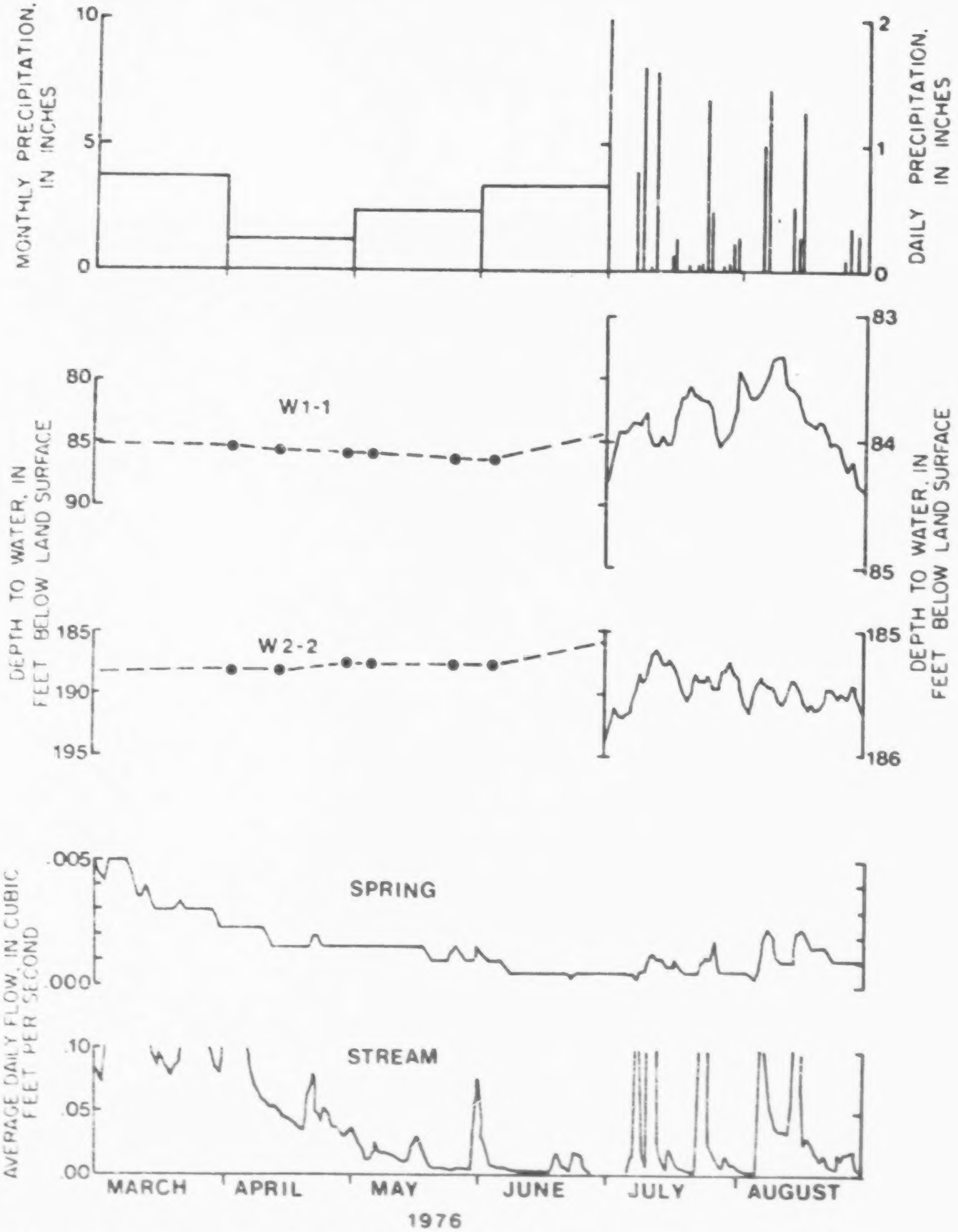


Figure 67. Graphs of Precipitation, Ground-Water Levels, Spring Flow, and Streamflow at C06 for part of 1976 (Graphs of Precipitation, Spring Flow, and Streamflow are Based on Preliminary Data from USDA-Science and Education Administration)

consisted of evapotranspiration along the stream plus base flow to the stream. Gaged streamflow at the mouth of the watershed (shown in Figure 67) included middle-aquifer base flow and top-aquifer spring flow as well as overland runoff.

2. Watershed M09

The ground-water divide for the top aquifer at M09 (above the clay that underlies the Meigs Creek (Sewickley) No. 9 coal bed) coincided with the surface drainage divide (Figure 68). Flow in the middle aquifer (above the clay that underlies the Pittsburgh No. 8 coal bed) included west-to-east underflow across the northern part of the watershed (Figure 69). Water in the middle aquifer in this area was part of a more extensive flow system which was away from the influence of the stream and was recharged and discharged mostly outside the watershed. The potentiometric head in the northwest part of the middle aquifer was above the overlying clay, at least during part of the year, so that confined conditions existed (Figure 69). In the deep aquifer, water movement was northerly; the top of this saturated zone was about 70 feet below the middle aquifer.

Computer simulations of the pumping test of well W5-2 produced time-drawdown relationships (Figure 70) comparable to that of the actual test. The best computer simulation used a hydraulic conductivity value of 1.0×10^{-7} ft/s, whereas an analysis by the type-curve method indicated a value of 3.1×10^{-7} ft/s.

Ground-water levels (representative hydrographs shown in Figure 71) fluctuated similarly to those at C06. Surface discharge from the top aquifer occurred as evapotranspiration and spring flow (one gaged site, Figures 16 and 19, and minor seepage areas). The gaged spring flow was a minimum rate of surface discharge from the top aquifer (evapotranspiration could have made the total rate significantly greater). Surface discharge from the middle aquifer was by evapotranspiration along the stream and base flow to the stream. Gaged streamflow (shown in Figure 71) included middle-aquifer base flow and top-aquifer spring flow as well as overland runoff.

3. Watershed J11

The top aquifer at J11 (Figure 72) was above the shaly clay that underlies the Waynesburg No. 11 coal bed; the middle aquifer (Figure 73) was above the shaly clay that underlies the Meigs Creek (Sewickley) No. 9 coal bed. Underflow did not seem significant in either aquifer. The top aquifer discharged water to the surface as evapotranspiration and at one ungaged spring; the middle aquifer discharged water as evapotranspiration and base flow. The two deepest wells penetrated mined-out openings in the Pittsburgh No. 8 coal bed and were dry; much of the No. 8 coal bed had been previously removed by underground mining. Deeper aquifers, below the No. 8 coal bed, have not been penetrated by

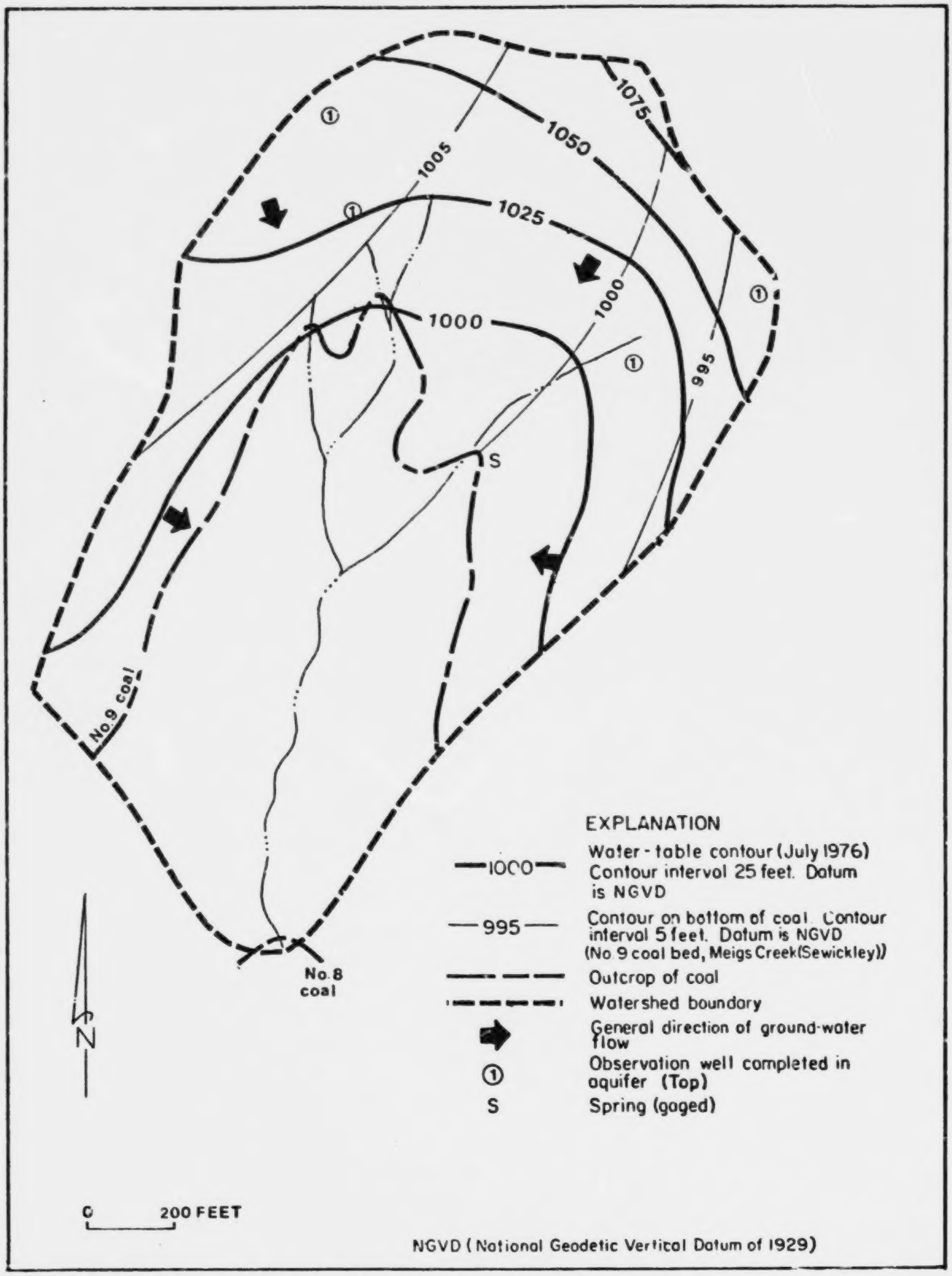

1075
1050
1005
1025
1000
1000
995
①
S
No.9 coal
No.8 coal
EXPLANATION
1000 Water-table contour (July 1976) Contour interval 25 feet. Datum is NGVD
995 Contour on bottom of coal. Contour interval 5 feet. Datum is NGVD (No. 9 coal bed, Meigs Creek (Sewickley))
Outcrop of coal
Watershed boundary
General direction of ground-water flow
① Observation well completed in aquifer (Top)
S Spring (gaged)
N
0 200 FEET
NGVD (National Geodetic Vertical Datum of 1929)

Figure 68. Potentiometric Surface and Base of Top Aquifer at M09

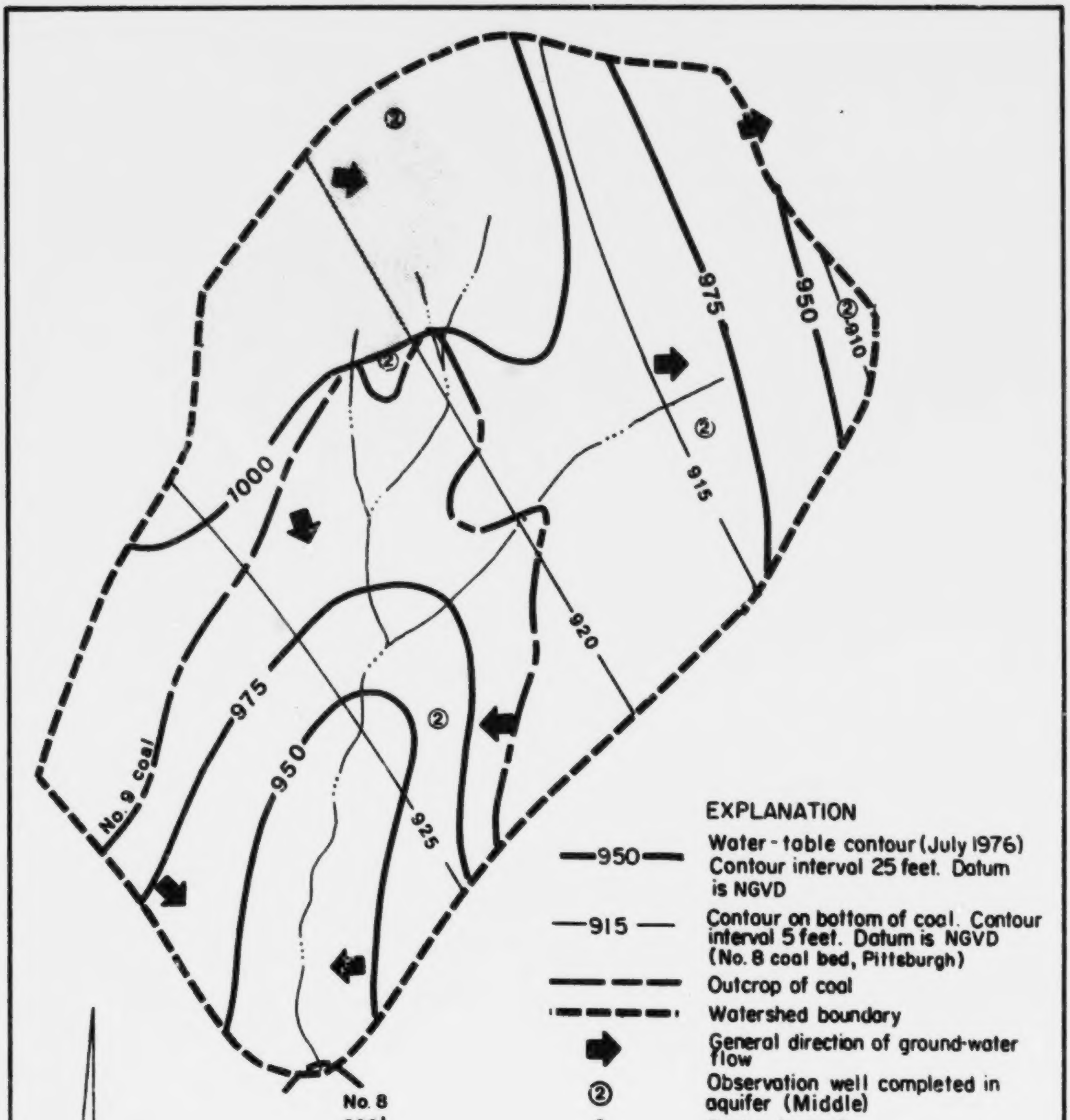

975
950
910
915
920
925
1000
975
950
No. 9 coal
No. 8 coal
EXPLANATION
—950— Water-table contour (July 1976) Contour interval 25 feet. Datum is NGVD
—915— Contour on bottom of coal. Contour interval 5 feet. Datum is NGVD (No. 8 coal bed, Pittsburgh)
Outcrop of coal
Watershed boundary
General direction of ground-water flow
② Observation well completed in aquifer (Middle)
S Spring (gaged)
Area of intermittent confined conditions
N
0 200 FEET
NGVD (National Geodetic Vertical Datum of 1929)

Figure 69. Potentiometric Surface and Base of Middle Aquifer at M09

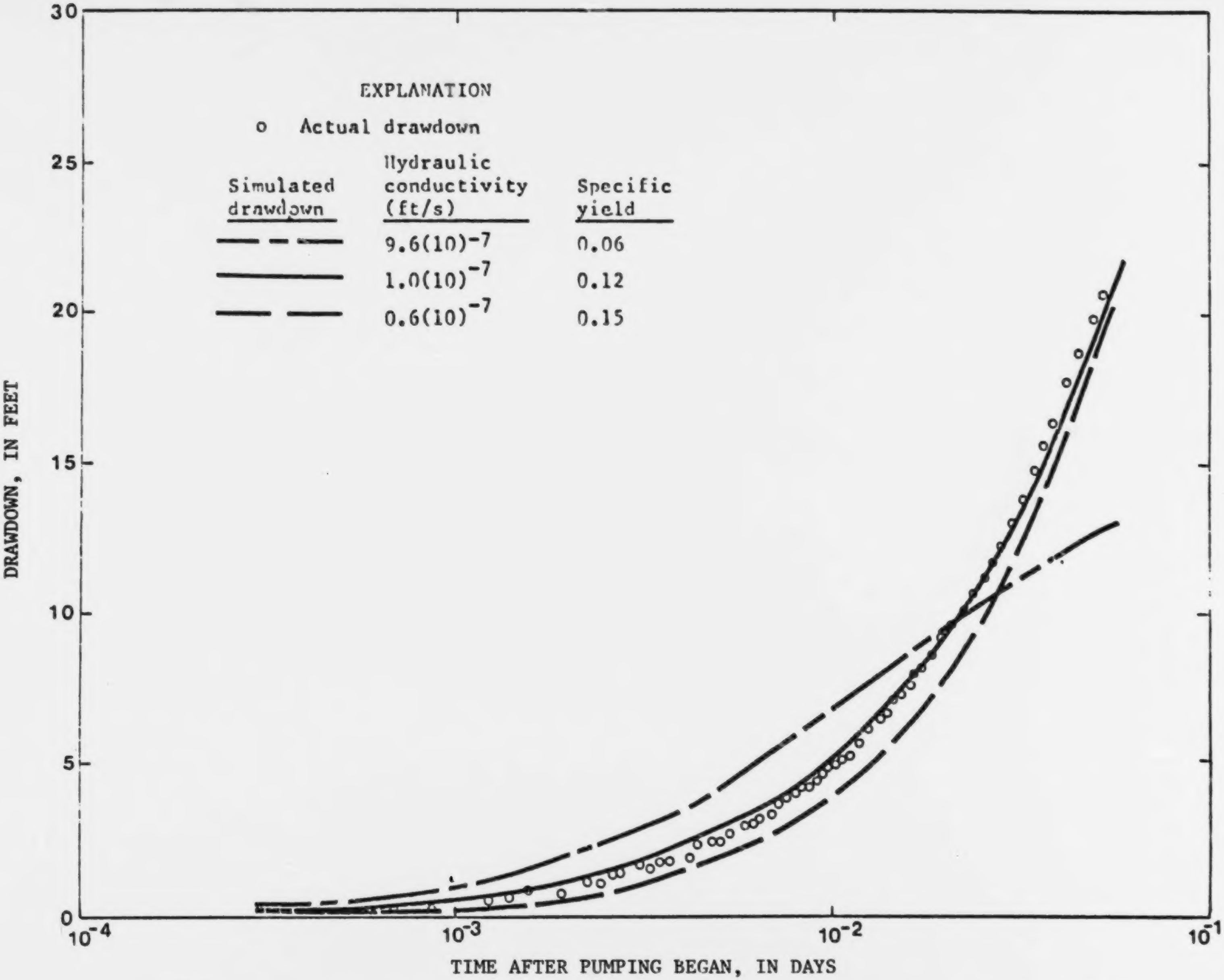


Figure 70. Drawdown Versus Time for Actual and Simulated Pumping Tests at Well W5-2 in Watershed M09

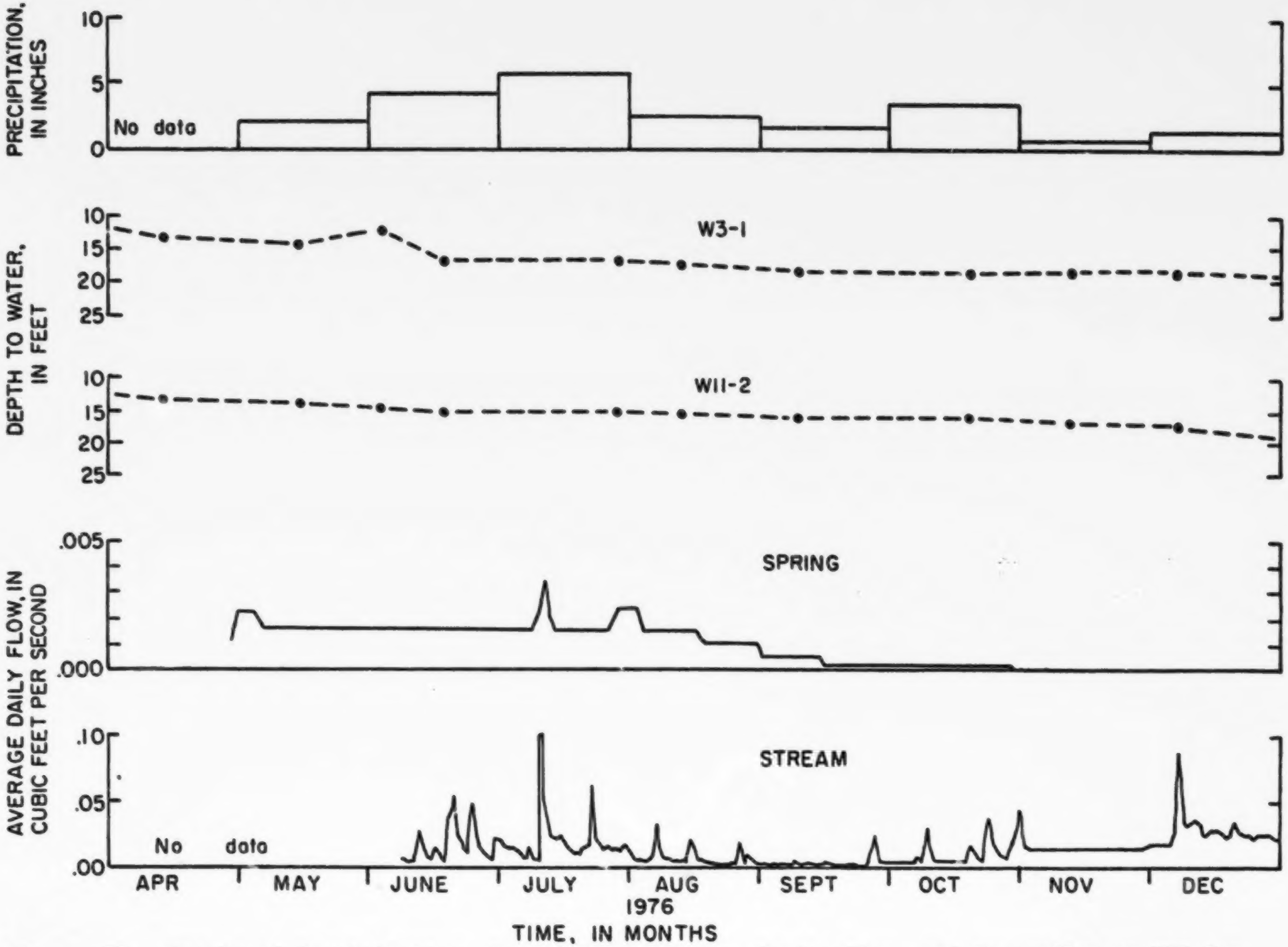


Figure 71. Graphs of Precipitation, Ground-Water Levels, Spring Flow, and Streamflow at M09 for Part of 1976 (Graphs of Precipitation, Spring Flow, and Streamflow are Based on Preliminary Data from USDA-Science and Education Administration)

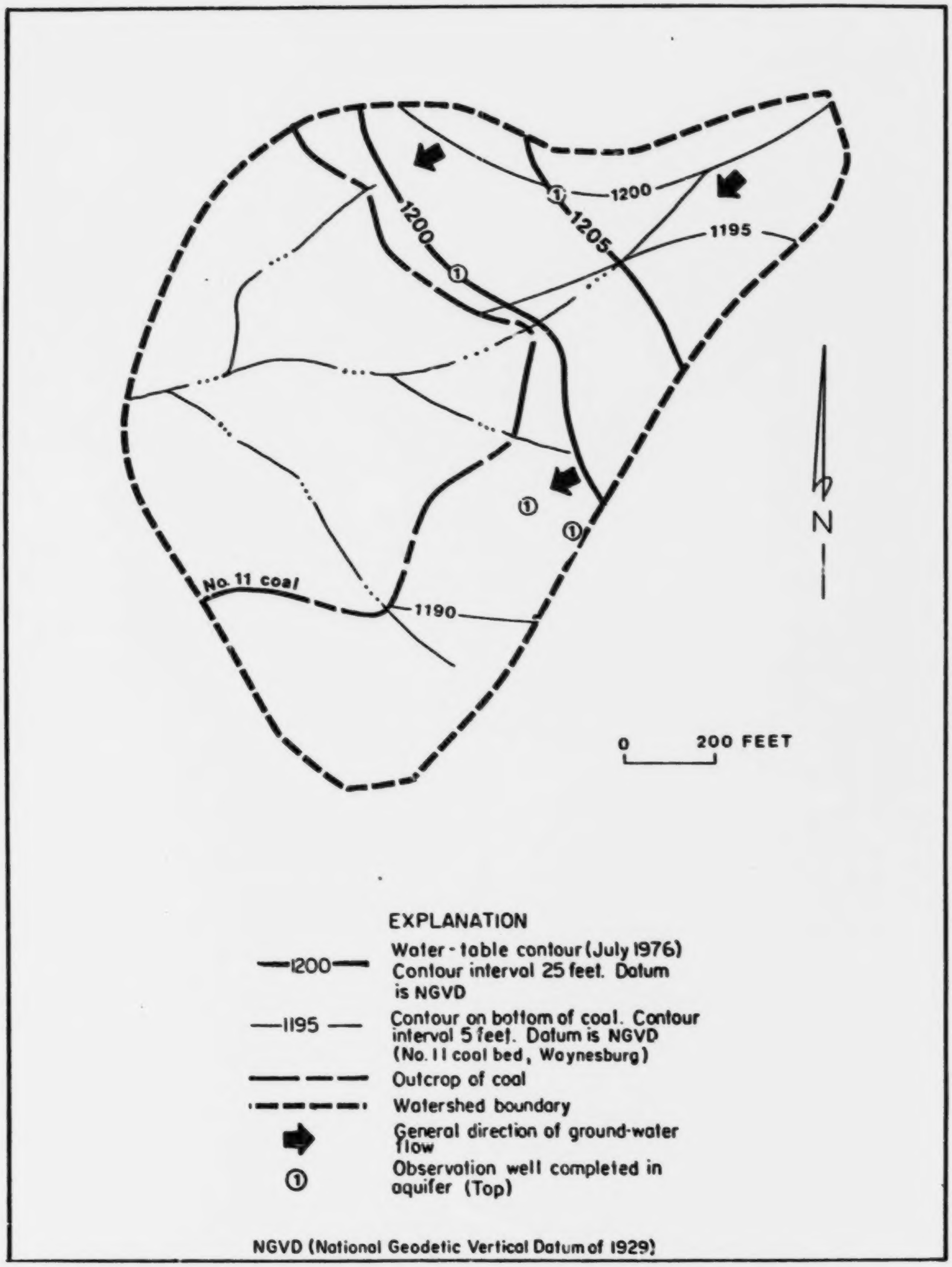

1200
1205
1200
1195
1190
No. 11 coal
①
N
0
200 FEET
EXPLANATION
1200 Water-table contour (July 1976) Contour interval 25 feet. Datum is NGVD
1195 Contour on bottom of coal. Contour interval 5 feet. Datum is NGVD (No. 11 coal bed, Waynesburg)
Outcrop of coal
Watershed boundary
General direction of ground-water flow
① Observation well completed in aquifer (Top)
NGVD (National Geodetic Vertical Datum of 1929)

Figure 72. Potentiometric Surface and Base of Top Aquifer at J11

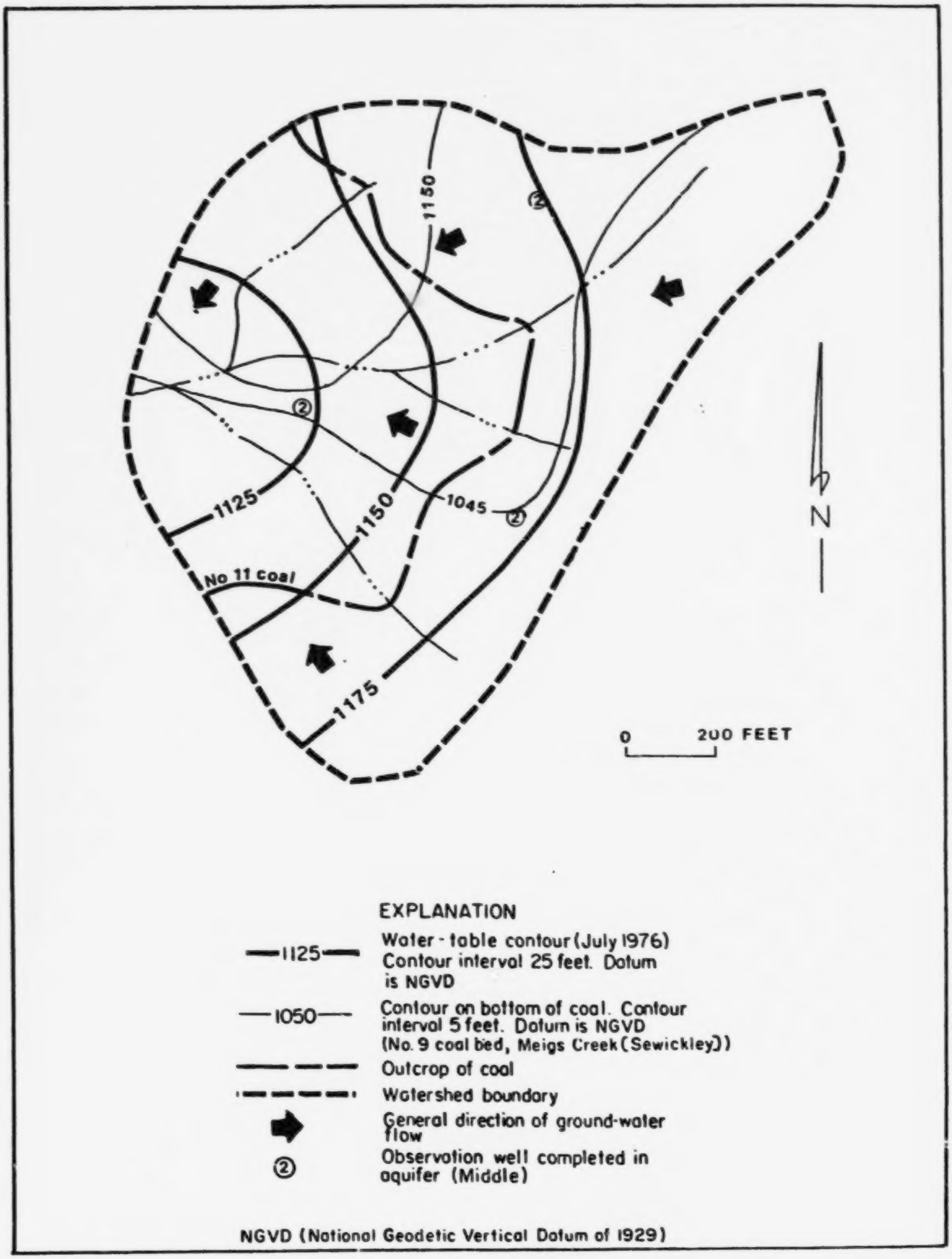

1150
②
1125
1150
1045
No 11 coal
1175
0
200 FEET
N
EXPLANATION
—1125— Water-table contour (July 1976) Contour interval 25 feet. Datum is NGVD
—1050— Contour on bottom of coal. Contour interval 5 feet. Datum is NGVD (No. 9 coal bed, Meigs Creek (Sewickley))
Outcrop of coal
Watershed boundary
General direction of ground-water flow
② Observation well completed in aquifer (Middle)
NGVD (National Geodetic Vertical Datum of 1929)

Figure 73. Potentiometric Surface and Base of Middle Aquifer at J11

drilling. More detailed description of the J11 ground-water system will be undertaken as premining data collection continues.

4. Watershed J08

The top aquifer at J08 was above the shale that underlies the Meigs Creek (Sewickley) No. 9 coal bed; the middle aquifer was above the shale that underlies the Pittsburgh No. 8 coal bed. As at J11, much of the No. 8 coal bed has been removed by underground mining. Definition of the flow systems was not possible because only one well was completed in each aquifer.

5. Watershed A06

The top aquifer at A06 (Figure 74) was above the clay that underlies the Middle Kittanning No. 6 coal bed; the middle aquifer (Figure 75) was above the clay that underlies the Brookville No. 4 coal bed. Surface discharge from the top aquifer was mainly as evapotranspiration; that from the middle aquifer was evapotranspiration, base flow to the stream, and at one gaged spring. Underflow out of the watershed to the northwest occurred in both aquifers, although flow was from the divide toward the coal outcrop at times in the top aquifer. In the deep aquifer water moved southward; the top of this saturated zone was about 20 feet below the middle aquifer. More detailed description of the A06 ground-water system will be undertaken as data collection continues.

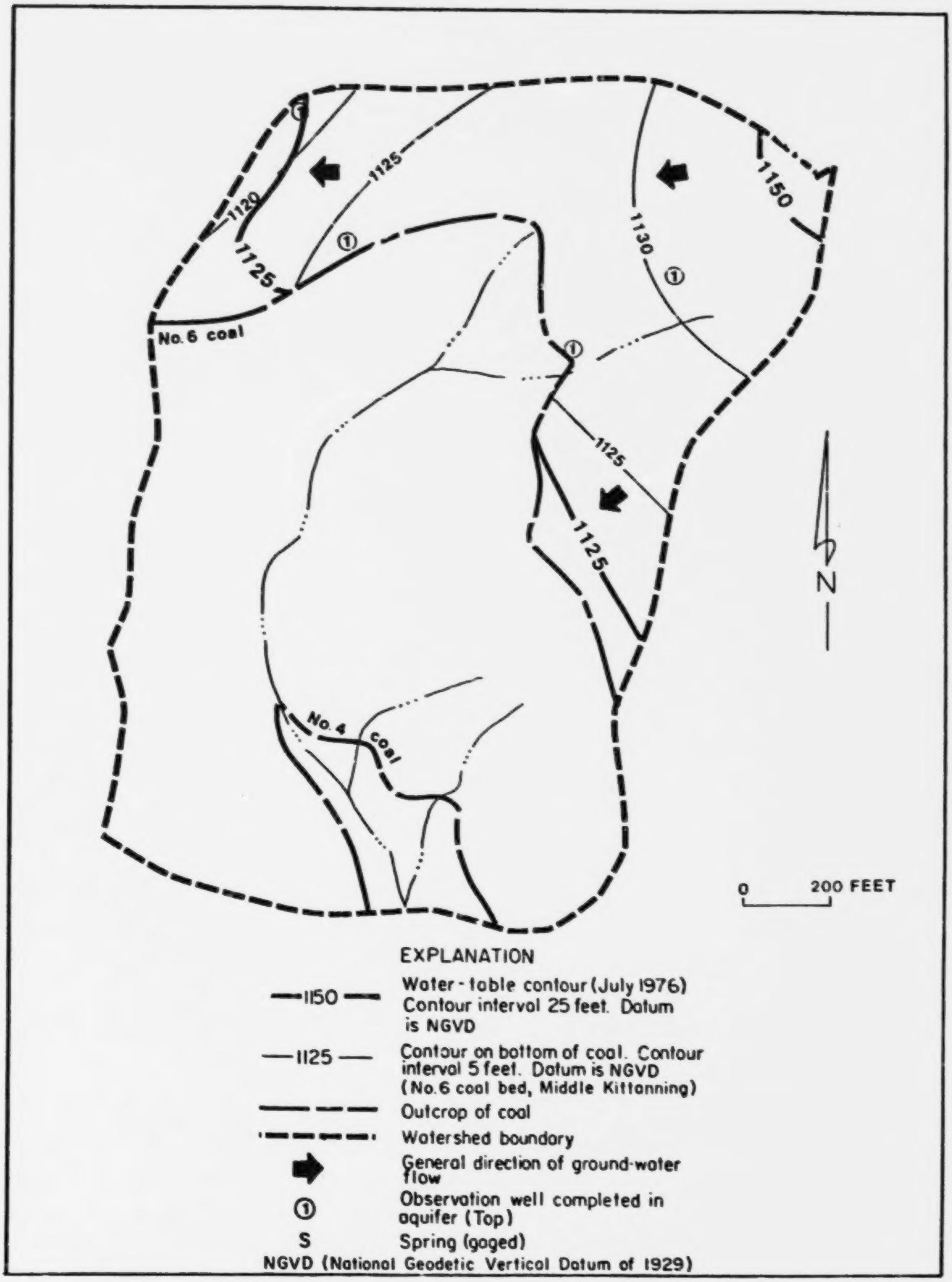

1120
1125
1125
①
①
No. 6 coal
1130
①
1150
①
1125
1125
No. 4 coal
N
0 200 FEET
EXPLANATION
—1150— Water-table contour (July 1976) Contour interval 25 feet. Datum is NGVD
—1125— Contour on bottom of coal. Contour interval 5 feet. Datum is NGVD (No. 6 coal bed, Middle Kittanning)
Outcrop of coal
Watershed boundary
General direction of ground-water flow
① Observation well completed in aquifer (Top)
S Spring (gaged)
NGVD (National Geodetic Vertical Datum of 1929)

Figure 74. Potentiometric Surface and Base of Top Aquifer at A06

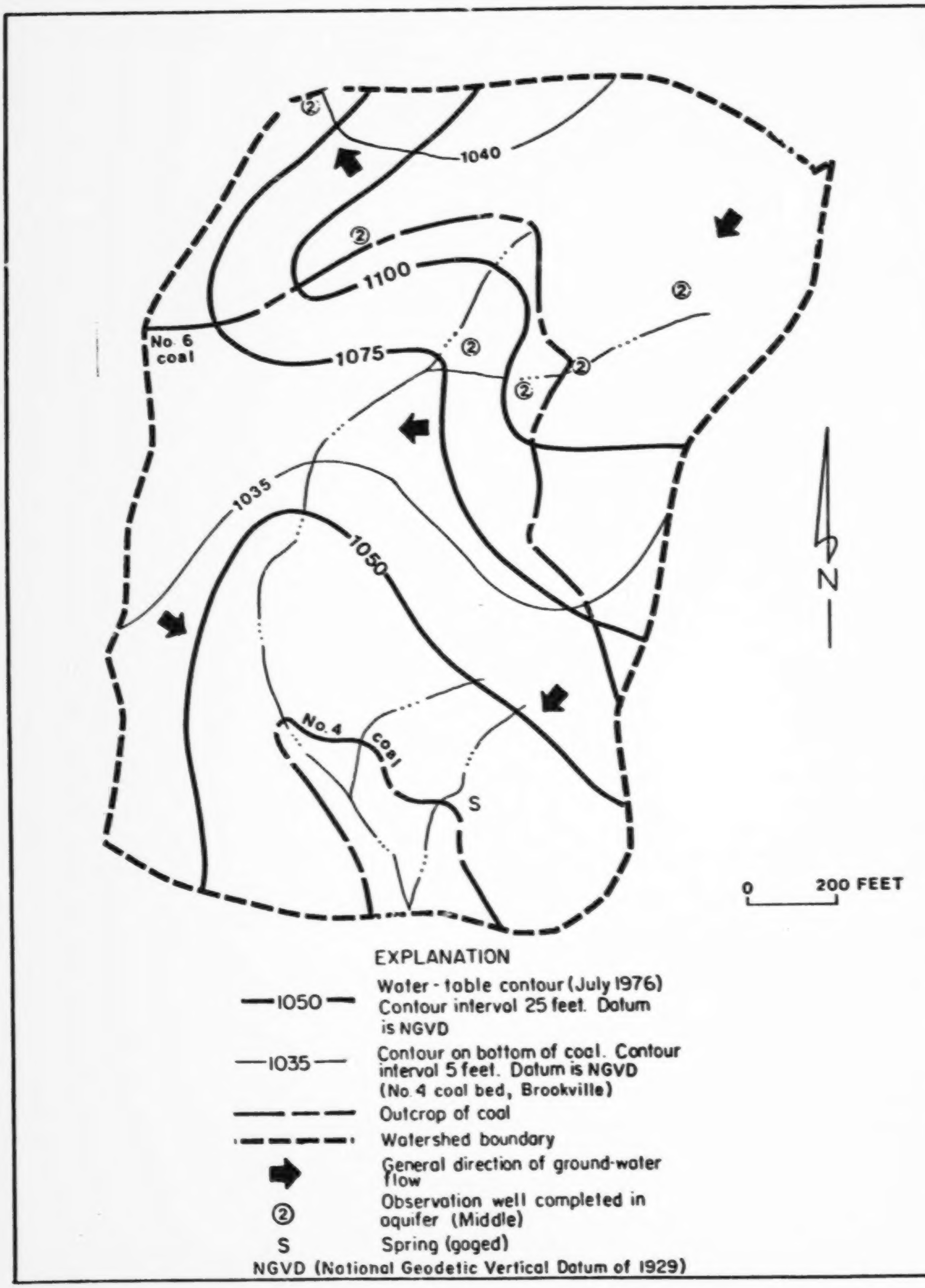

1040
1100
No. 6 coal
1075
1035
1050
No. 4 coal
S
N
0 200 FEET
EXPLANATION
1050 Water-table contour (July 1976) Contour interval 25 feet. Datum is NGVD
1035 Contour on bottom of coal. Contour interval 5 feet. Datum is NGVD (No. 4 coal bed, Brookville)
Outcrop of coal
Watershed boundary
General direction of ground-water flow
② Observation well completed in aquifer (Middle)
S Spring (gaged)
NGVD (National Geodetic Vertical Datum of 1929)

Figure 75. Potentiometric Surface and Base of Middle Aquifer at A06

VI. CROUND-WATER QUALITY

A. Experimental Procedures

Water-samples were collected on a quarterly basis from wells and springs for determination of chemical quality. Early methods of sample collection (including all of the samples from C06 and M09) were inconsistent because of problems in obtaining samples from wells. Use of a 4-inch diameter submersible pump commonly resulted in the well being rapidly pumped dry and collection of a sediment-contaminated sample. Eight "grab" samples were collected (dipped from the well), but these were not necessarily representative of water in the aquifer. In October, 1976, a small gas-operated membrane pump was used in order to decrease the discharge. Use of the small pump also permitted samples to be obtained from the deepest wells in the study watersheds. The wells were pumped about 5 minutes, allowed to recover, then pumped again to collect the sample. Throughout the previously discussed pumping tests, specific conductance changed very little, suggesting that representative samples were being obtained.

Temperature, specific conductance, pH, and alkalinity were determined in the field. Samples were kept chilled until laboratory determinations of the remaining parameters were made. Part of each sample was filtered in the field for determination of dissolved parameters. Procedures used for laboratory analysis are those outlined by American Public Health Association et al (1975). Metal concentrations were determined by atomic absorption methods.

Reference in this report to recommended limits of concentration are based on drinking-water standards of the U. S. Environmental Protection Agency (1977).

B. Results and Discussion

Chemical analyses of water from wells and springs for Watersheds C06, M09, J11, J08, and A06 are summarized in Tables 76-80. Chemical quality of ground water varied considerably between study watersheds, between aquifers, and within most aquifers. Results of water analyses from the same well also varied with time, at least partly because of the inconsistent sampling techniques. This was evident particularly in the total (dissolved plus suspended) concentrations of heavy metal and organic constituents, which, because of their high absorptive capacity, were higher in sediment-contaminated samples.

Despite the variations, much of the ground water could be characterized as calcium bicarbonate type. Sulfate, chloride, and sodium were predominant in some places, especially in parts of the middle and deep aquifers. The chemical diversity of these deeper waters was probably a result of: (1) variable lithology, from which the water acquired its chemical characteristics; and (2) variable hydraulic conductivity,

Table 76. Chemical Analyses of Ground Water from C06 Collected November 1975 - October 1976 (Based on All Premining Data: Top Aquifer - 18 Samples from 4 Wells and 2 Springs; Middle Aquifer - 9 Samples from 4 Wells; Deep Aquifer - 5 Samples from 2 Wells).

Parameter	Unit	Concentration or value					
		Top aquifer		Middle aquifer		Deep aquifer	
		Range	Median	Range	Median	Range	Median
Alkalinity as $CaCO_3$	mg/L	21-135	92	125-284	222	97-351	208
Aluminum Total	ug/L	60-50000	920	20-5600	2100	50-9100	1000
Antimony Total	ug/L	0-2	0	0-1	0	0-5	1
Arsenic Total	ug/L	0-43	3	0-5	1	0-23	5
Barium Total	ug/L	0-1100	100	0-300	100	0-200	200
Bicarbonate	mg/L	25-164	112	152-346	271	118-428	132
Cadmium Total	ug/L	0-62	5	1-34	7	2-14	4
Calcium Dissolved	mg/L	3.1-53	26	3.2-90	38	3.0-28	25
Carbon Dioxide	mg/L	1.7-154	35	13-122	35	4.7-49	17
Carbon Total Organic	mg/L	1.3-27	4.1	0.2-8.6	3.0	0.1-45	2.3
Carbonate	mg/L	0-0	0	0-0	0	0-0	0
Chloride Dissolved	mg/L	1.0-91	2.3	1.1-9.0	3.9	1.2-70	3.8
Chromium Total	ug/L	0-110	<10	<10-60	<10	<10-30	10
Color	Pt/Co	1-46	3	1-8	1	1-170	3
Copper Total	ug/L	0-950	10	0-110	10	0-190	10
Cyanide	mg/L	0.00-0.01	0.00	0.00-0.00	0.00	0.00-1.0	0.00
Fluoride Dissolved	mg/L	0.1-1.6	0.2	0.3-0.9	0.3	0.2-1.7	0.3
Hardness Noncarbonate	mg/L	0-65	32	0-72	36	0-31	16
Hardness Total	mg/L	11-170	115	14-330	190	12-130	120
Hydrogen Sulfide	mg/L	0.0-0.3	0.0	0.0-0.2	0.0	0.0-0.2	0.0
Iron Dissolved	ug/L	10-2300	130	40-2000	930	10-630	50
Iron Total	ug/L	120-170000	5400	1200-27000	7600	1700-32000	6600
Lead Total	ug/L	0-400	22	2-44	15	3-120	13
Magnesium Dissolved	mg/L	0.8-15	0.9	1.4-26	16	1.2-15	14
Manganese Dissolved	ug/L	0-930	140	20-710	270	20-110	60
Manganese Suspended	ug/L	0-70000	360	0-210	120	10-500	120
Manganese Total	ug/L	0-70000	690	40-840	270	70-540	140
Mercury Total	ug/L	<0.5-<0.5	<0.5	<0.5-2.0	<0.5	<0.5-1.1	<0.5
Nickel Total	ug/L	2-550	19	1-20	13	2-100	15
Nitrogen NH_4 as N Total	mg/L	0.00-1.3	0.04	0.00-0.53	0.31	0.00-0.43	0.01
NO_2+NO_3 as N	mg/L	0.02-0.73	0.07	0.01-0.39	0.04	0.05-0.10	0.07
pH (field)		6.0-8.2	6.8	6.3-7.6	7.2	6.6-8.1	7.1
Phenols	ug/L	0-8	0	0-4	0	0-7	0
Phosphorus Total as P	mg/L	0.08-3.8	0.10	0.03-0.12	0.06	0.02-0.54	0.08
Phosphorus Total PO_4	mg/L	0.06-12	0.32	0.09-0.37	0.18	0.06-1.7	0.25
Potassium Dissolved	mg/L	1.0-4.9	1.6	1.7-4.8	3.3	0.4-7.4	0.9
Residue Dissolved (calculated sum)	mg/L	--	--	--	--	--	--
Residue Dissolved	tons/acre-ft	--	--	--	--	--	--
Sodium adsorption ratio		0.1-29	0.2	0.3-14	0.8	0.1-31	0.1
Selenium Total	ug/L	0-6	0	0-0	0	0-29	0
Silica Dissolved	mg/L	--	--	--	--	--	--
Silver Total	ug/L	0-1	0	0-2	0	0-3	0
Sodium Dissolved	mg/L	1.0-220	6.4	7.7-120	21	3.3-250	3.8
Sodium (percent)	%	3-97	11	11-94	21	5-97	6
Specific Conductance (field)	umhos/cm	120-520	288	280-905	600	258-1110	278
Strontium Total	ug/L	30-240	90	100-920	280	50-140	70
Sulfate Dissolved	mg/L	11-80	36	2.9-160	48	8.2-80	20
Water Temperature (°C)	°C	7.0-18	13	11.0-14.0	12.5	12.0-17.0	12.5
Zinc Total	ug/L	10-800	90	20-1500	220	20-310	90

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Table 77. Chemical Analyses of Ground Water from M09 Collected April - November 1976. (Based on All Premining Data: Top Aquifer - 12 Samples from 4 Wells and 1 Spring; Middle Aquifer - 14 Samples from 6 Wells; Deep Aquifer - 3 Samples from 2 Wells).

Parameter	Unit	Concentration or value					
		Top aquifer		Middle aquifer		Deep aquifer	
		Range	Median	Range	Median	Range	Median
Alkalinity as CaCO3	mg/L	167-373	314	234-499	373	222-559	432
Aluminum Total	ug/l	10-8300	2000	50-58000	3100	3400-60000	13000
Antimony Total	ug/L	0-2	0	0-3	0	0-1	0
Arsenic Total	ug/L	0-64	4	0-130	9	11-45	25
Barium Total	ug/L	200-1800	200	100-12000	300	100-3000	200
Bicarbonate	mg/L	204-455	399	94-608	455	246-602	444
Cadmium Total	ug/L	1-20	6	0-13	4	5-14	11
Calcium Dissolved	mg/L	58-81	70	4.1-92	40	3.2-230	4.9
Carbon Dioxide	mg/L	6.2-119	18	0.1-66	8.2	0.7-1.4	1.3
Carbon Total Organic	mg/L	0.5-40	2.4	0.5-6.5	3.2	5.6-30	12.2
Carbonate	mg/L	0-0	0	0-94	0	12-41	39
Chloride Dissolved	mg/L	1.5-5.6	3.0	1.3-4100	8.4	530-9900	590
Chromium Total	ug/L	<10-130	<10	<10-160	10	10-150	50
Color	Pt/Co	1-3	2	1-40	2	2-370	160
Copper Total	ug/L	0-30	10	10-60	10	10-50	20
Cyanide	mg/L	0.00-0.00	0.00	0.00-2.0	0.00	0.01-2.0	1.0
Fluoride Dissolved	mg/L	0.2-0.3	0.2	0.2-2.9	1.3	3.6-5.5	3.6
Hardness Noncarbonate	mg/L	0-72	14	0-46	0	0-600	0
Hardness Total	mg/L	210-450	315	18-350	100	12-820	17
Hydrogen Sulfide	mg/L	0.0-5.8	0.0	0.0-0.3	0.0	0.0-0.0	0.0
Iron Dissolved	ug/L	0-170	40	10-470	40	40-90	60
Iron Total	ug/L	90-160000	4200	120-140000	5400	7100-89000	19000
Lead Total	ug/L	0-300	18	2-160	17	27-280	41
Magnesium Dissolved	mg/L	15-59	33	1.4-39	8.6	0.9-59	1.1
Manganese Dissolved	ug/L	0-290	20	0-240	20	10-80	10
Manganese Suspended	ug/L	0-1400	110	0-1700	40	40-1100	160
Manganese Total	ug/L	20-1400	140	20-1700	100	50-1200	170
Mercury Total	ug/L	<0.5-<0.5	<0.5	<0.5-0.9	<0.5	<0.5-0.9	<0.5
Nickel Total	ug/L	1-240	10	2-340	12	13-350	53
Nitrogen NH4 as N Total	mg/L	0.00-0.04	0.01	0.00-1.2	0.20	0.14-3.6	0.38
NO2+NO3 as N	mg/L	0.01-0.63	0.12	0.00-0.36	0.03	0.03-0.48	0.03
pH (field)		6.5-7.8	7.6	7.0-9.7	7.8	8.8-8.9	8.8
Phenols	ug/L	0-120	2	0-68	4	0-5	0
Phosphorus Total as P	mg/L	0.02-0.59	0.06	0.03-0.93	0.04	0.11-15	0.38
Phosphorus Total PO4	mg/L	0.06-1.8	0.20	0.09-2.9	0.14	0.34-46	1.2
Potassium Dissolved	mg/L	0.5-2.7	1.6	0.8-10	1.6	1.5-24	1.8
Residue Dissolved (calculated sum)	mg/L	267-402	367	329-1700	431	1400-1400	1400
Residue Dissolved	tons/acre-ft	--	--	--	--	46-46	46
Sodium adsorption ratio		0.1-0.7	0.2	0.2-92	9.9	49-71	66
Selenium Total	ug/L	0-23	2	0-4	2	0-78	8
Silica Dissolved	mg/L	9.8-19	11	6.8-17	13	2.9-2.9	2.9
Silver Total	ug/L	0-0	0	0-1	0	0-0	0
Sodium Dissolved	mg/L	4.0-28	5.4	9.3-2900	120	560-3200	620
Sodium (percent)	%	2-16	5	6-97	88	89-99	99
Specific Conductance (field)	umhos/cm	430-890	545	560-12400	796	1750-26800	2700
Strontium Total	ug/L	250-2600	720	330-7600	690	190-25000	360
Sulfate Dissolved	mg/L	30-122	40	9.0-94	36	31-180	36
Water Temperature (°C)	°C	10.5-16.0	13.5	12.0-14.5	13.0	11.5-15.0	13.0
Zinc Total	ug/L	10-160	80	20-210	70	20-80	30

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Table 78. Chemical Analyses of Ground Water from J11 Collected August 1976 - February 1978. (Top Aquifer - 17 Samples from 4 Wells; Middle Aquifer - 15 Samples from 3 Wells)

Parameter	Unit	Concentration or value			
		Top aquifer		Middle aquifer	
		Range	Median	Range	Median
Alkalinity as CaCO3	mg/L	23-346	157	254-386	295
Aluminum Total	ug/l	10-1200	190	30-1100	280
Antimony Total	ug/L	0-1	0	0-1	0
Arsenic Total	ug/L	0-3	1	0-15	1
Barium Total	ug/L	0-300	100	0-500	100
Bicarbonate	mg/L	28-422	192	310-471	360
Cadmium Total	ug/L	0-33	1	0-3	0
Calcium Dissolved	mg/L	48-120	80	15-100	57
Carbon Dioxide	mg/L	2.7-56	26	3.9-53	16
Carbon Total Organic	mg/L	2.1-9.2	5.4	2.8-8.5	5.6
Carbonate	mg/L	0-0	0	0-0	0
Chloride Dissolved	mg/L	9.5-55	14	8.8-29	14
Chromium Total	ug/L	<10-10	<10	<10-10	<10
Color	Pt/Co	0-5	2	0-5	2
Copper Total	ug/L	0-50	10	0-20	10
Cyanide	mg/L	0.00-2.0	0.00	0.00-0.00	0.00
Fluoride Dissolved	mg/L	0.1-0.2	0.1	0.1-2.0	0.2
Hardness Noncarbonate	mg/L	55-210	96	0-55	0
Hardness Total	mg/L	170-430	270	61-390	240
Hydrogen Sulfide	mg/L	0.0-0.3	0.0	0.0-0.2	0.0
Iron Dissolved	ug/L	0-170	30	0-80	10
Iron Total	ug/L	30-11000	800	20-210000	2200
Lead Total	ug/L	2-100	21	2-19	10
Magnesium Dissolved	mg/L	9.3-31	16	5.8-33	23
Manganese Dissolved	ug/L	0-720	30	0-40	10
Manganese Suspended	ug/L	0-450	30	0-1700	110
Manganese Total	ug/L	20-780	120	10-1700	120
Mercury Total	ug/L	0.0-<0.5	0.0	0.0-<0.5	0.0
Nickel Total	ug/L	3-30	10	1-18	5
Nitrogen NH4 as N Total	mg/L	0.01-0.21	0.01	0.00-0.27	0.03
NO2+NO3 as N	mg/L	0.01-11	0.13	0.01-0.52	0.02
pH (field)		5.9-7.7	7.2	7.1-8.2	7.5
Phenols	ug/L	0-42	4	0-68	0
Phosphorus Total as P	mg/L	0.00-0.20	0.02	0.00-0.12	0.06
Phosphorus Total PO4	mg/L	0.00-0.61	0.04	0.00-0.37	0.06
Potassium Dissolved	mg/L	1.5-2.2	1.7	1.4-2.5	2.2
Residue Dissolved (calculated sum)	mg/L	252-416	335	340-499	424
Residue Dissolved	tons/acre-ft	0.35-0.57	0.45	0.46-0.68	0.65
Sodium adsorption ratio		0.1-0.4	0.2	0.7-9.4	1.6
Selenium Total	ug/L	0-3	0	0-1	0
Silica Dissolved	mg/L	10-19	15	10-18	13
Silver Total	ug/L	0-3	0	0-0	0
Sodium Dissolved	mg/L	5.6-13	8.0	27-170	60
Sodium (percent)	%	3-12	7	13-85	32
Specific Conductance (field)	umhos/cm	405-830	550	570-817	605
Strontium Total	ug/L	200-420	360	300-1800	1500
Sulfate Dissolved	mg/L	24-190	85	22-85	47
Water Temperature (^{o}C)	^{o}C	3.0-14.0	12.5	9.0-13.5	12.0
Zinc Total	ug/L	30-150	70	30-170	50

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Table 79. Chemical Analyses of Ground Water from J08 Collected March 1977 - February 1978. (Top Aquifer - 3 Samples from 1 Well; Middle Aquifer - 3 Samples from 1 Well; Deep Aquifer - 2 Samples from 1 Well).

Parameter	Unit	Concentration or value					
		Top aquifer		Middle aquifer		Deep aquifer	
		Range	Median	Range	Median	Range	Median
Alkalinity as CaCO3	mg/L	237-246	239	804-845	837	589-627	608
Aluminum Total	ug/l	650-1500	1400	790-1300	1000	220-240	230
Antimony Total	ug/L	0-0	0	0-0	0	0-0	0
Arsenic Total	ug/L	0-3	1	2-3	2	2-2	2
Barium Total	ug/L	0-200	200	100-200	200	4000-6000	5000
Bicarbonate	mg/L	289-300	292	980-1030	1020	718-764	741
Cadmium Total	ug/L	0-0	0	0-2	0	0-3	2
Calcium Dissolved	mg/L	120-140	130	7.3-22	10	58-64	61
Carbon Dioxide	mg/L	12-18	12	13-50	16	31-36	34
Carbon Total Organic	mg/L	6.3-8.1	7.3	4.8-8.5	5.9	5.2-8.4	6.8
Carbonate	mg/L	0-0	0	0-0	0	0-0	0
Chloride Dissolved	mg/L	2.9-3.9	3.4	230-320	240	5600-5600	5600
Chromium Total	ug/L	<10-20	10	<10-20	10	< 20-20	< 20
Color	Pt/Co	0-0	0	0-0	0	0-20	10
Copper Total	ug/L	3-6	5	17-18	17	20-21	20
Cyanide	mg/L	0.00-0.00	0.00	0.00-0.00	0.00	0.00-0.01	0.00
Fluoride Dissolved	mg/L	0.1-0.2	0.2	3.9-4.8	4.6	0.3-0.3	0.3
Hardness Noncarbonate	mg/L	240-310	260	0-0	0	0-0	0
Hardness Total	mg/L	490-550	500	26-79	38	280-300	290
Hydrogen Sulfide	mg/L	0.0-0.2	0.0	0.0-0.4	0.0	0.0-0.3	0.2
Iron Dissolved	ug/L	10-20	10	10-40	10	50-120	80
Iron Total	ug/L	1300-2500	1700	1600-8800	3000	7400-7500	7400
Lead Total	ug/L	4-29	9	60-76	60	30-260	180
Magnesium Dissolved	mg/L	42-48	46	2.5-5.9	3.1	33-35	34
Manganese Dissolved	ug/L	0-10	0	0-20	10	40-60	50
Manganese Suspended	ug/L	40-70	50	30-100	30	50-70	60
Manganese Total	ug/L	40-80	50	40-100	50	90-130	110
Mercury Total	ug/L	0.0-0.0	0.0	0.0-0.0	0.0	0.0-0.2	0.1
Nickel Total	ug/L	3-4	3	7-19	8	4-8	6
Nitrogen NH4 as N Total	mg/L	0.01-0.4	0.03	0.02-0.35	0.04	2.1-2.2	2.2
NO2+NO3 as N	mg/L	0.14-0.28	0.26	0.26-0.38	0.35	0.00-0.01	0.00
pH (field)		7.4-7.6	7.6	7.5-8.1	8.0	7.5-7.6	7.6
Phenols	ug/L	0-12	0	0-43	22	0-0	0
Phosphorus Total as P	mg/L	0.03-0.11	0.06	0.01-0.10	0.03	0.05-0.10	0.08
Phosphorus Total PO4	mg/L	0.09-0.34	0.18	0.03-0.31	0.09	0.15-0.31	0.23
Potassium Dissolved	mg/L	2.7-2.8	2.7	3.3-5.3	3.5	13-13	13
Residue Dissolved (calculated sum)	mg/L	590-658	610	1380-1510	1490	9900-9910	9900
Residue Dissolved	tons/acre-ft	0.80-0.89	0.83	1.88-2.05	2.03	13.5-13.5	13.5
Sodium adsorption ratio		0.2-0.2	0.2	27-44	43	95-99	97
Selenium Total	ug/L	0-2	1	0-0	0	0-0	0
Silica Dissolved	mg/L	9.9-11	10	5.0-6.3	5.1	6.9-7.2	7.0
Silver Total	ug/L	0-0	0	0-0	0	0-0	0
Sodium Dissolved	mg/L	9.0-10	9.3	540-600	560	3800-3800	3800
Sodium (percent)	%	3-4	4	93-97	97	96-97	96
Specific Conductance (field)	umhos/cm	840-952	860	2300-2400	2350	15000-15100	15000
Strontium Total	ug/L	1700-2300	2300	480-700	630	9200-10000	9600
Sulfate Dissolved	mg/L	250-300	270	65-170	74	13-33	22
Water Temperature (°C)	°C	11.5-13.5	12.5	14.0-15.5	15.0	13.0-15.5	14.0
Zinc Total	ug/L	40-70	50	30-60	40	160-220	190

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Table 80. Chemical Analyses of Ground Water from A06 Collected November 1975 - February 1978. (Top Aquifer - 9 Samples from 3 Wells; Middle Aquifer - 34 Samples from 6 Wells and 1 Spring; Deep Aquifer - 10 Samples from 2 Wells).

Parameter	Unit	Concentration or value					
		Top aquifer		Middle aquifer		Deep aquifer	
		Range	Median	Range	Median	Range	Median
Alkalinity as CaCO3 ------	mg/L	73-197	161	31-533	167	325-931	569
Aluminum Total -----------	ug/l	40-13000	800	0-1900	100	0-740	100
Antimony Total -----------	ug/L	0-1	0	0-1	0	0-1	0
Arsenic Total ------------	ug/L	0-13	4	0-300	1	0-2	1
Barium Total -------------	ug/L	0-200	100	0-500	100	0-300	100
Bicarbonate --------------	mg/L	89-240	196	38-650	204	396-808	556
Cadmium Total ------------	ug/L	0-32	0	0-33	0	0-2	0
Calcium Dissolved --------	mg/L	22-61	54	33-110	52	1.1-130	48
Carbon Dioxide -----------	mg/L	6.3-57	21	12-221	36	0.9-42	7.6
Carbon Total Organic -----	mg/L	4.2-9.8	8.7	0.2-13	5.4	1.2-12	6.4
Carbonate ----------------	mg/L	0-0	0	0-0	0	0-161	62
Chloride Dissolved -------	mg/L	3.2-4.8	3.9	1.4-23	2.0	3.9-67	30
Chromium Total -----------	ug/L	< 10-20	10	< 10-20	< 10	< 10-40	10
Color --------------------	Pt/Co	0-10	5	0-10	4	2-22	8
Copper Total -------------	ug/L	0-16	7	0-50	6	0-12	5
Cyanide ------------------	mg/L	0.00-2.0	0.00	0.00-0.01	0.00	0.00-1.0	0.00
Fluoride Dissolved -------	mg/L	0.1-0.3	0.2	0.2-0.5	0.3	0.2-5.0	1.2
Hardness Noncarbonate ----	mg/L	0-57	38	0-170	34	0-260	30
Hardness Total -----------	mg/L	87-230	200	83-360	210	3-580	210
Hydrogen Sulfide ---------	mg/L	0.0-0.3	0.0	0.0-2.0	0.2	0.0-2.0	0.2
Iron Dissolved -----------	ug/L	10-36000	30	0-26000	1000	10-5700	980
Iron Total ---------------	ug/L	20-42000	5800	20-26000	7000	3900-15000	6000
Lead Total ---------------	ug/L	0-16	8	0-62	5	0-12	8
Magnesium Dissolved ------	mg/L	7.7-19	17	10-35	19	0.1-62	22
Manganese Dissolved ------	ug/L	20-850	240	0-1400	240	10-120	60
Manganese Suspended ------	ug/L	0-2100	170	0-340	20	10-50	20
Manganese Total ----------	ug/L	130-2400	530	10-1400	300	20-130	90
Mercury Total ------------	ug/L	0.0-1.1	0.0	0.0-3.7	<0.5	0.0-2.1	< 0.5
Nickel Total -------------	ug/L	6-19	11	0-190	7	1-8	6
Nitrogen NH4 as N Total --	mg/L	0.01-0.17	0.05	0.00-3.3	0.18	0.48-3.7	1.8
NO2+NO3 as N -------------	mg/L	0.01-4.5	0.06	0.00-21	0.01	0.00-0.01	0.00
pH (field) ---------------		6.4-7.7	7.2	5.7-7.5	7.0	7.2-9.3	8.3
Phenols ------------------	ug/L	0-26	8	0-140	1	0-110	4
Phosphorus Total as P ----	mg/L	0.02-0.12	0.07	0.01-0.53	0.05	0.01-0.13	0.02
Phosphorus Total PO4 -----	mg/L	0.06-0.37	0.21	0.03-1.6	0.15	0.03-0.40	0.08
Potassium Dissolved ------	mg/L	1.7-3.5	2.0	2.3-12	3.6	2.4-18	8.4
Residue Dissolved (calculated sum) -------	mg/L	198-272	254	180-1170	351	984-1460	1180
Residue Dissolved --------	tons/acre-ft	0.27-0.37	0.35	0.24-1.59	0.48	1.34-1.99	1.60
Sodium adsorption ratio --		0.2-0.3	0.2	0.1-7.5	0.7	4.0-98	39
Selenium Total -----------	ug/L	0-1	0	0-8	0	0-1	0
Silica Dissolved ---------	mg/L	5.6-17	16	5.3-17	9.6	1.9-11	5.7
Silver Total -------------	ug/L	0-0	0	0-1	0	0-0	0
Sodium Dissolved ---------	mg/L	4.7-10	7.7	4.1-300	24	210-440	350
Sodium (percent) ---------	%	7-13	8	5-67	22	45-99	80
Specific Conductance (field) ---------------	umhos/cm	263-460	410	365-1800	535	1170-1970	1750
Strontium Total ----------	ug/L	100-230	170	140-2500	330	50-3600	1200
Sulfate Dissolved --------	mg/L	46-60	53	58-520	130	4.8-830	380
Water Temperature (°C) ---	°C	7.5-16.0	13.0	5.0-16	12.0	9.0-14.5	12.0
Zinc Total ---------------	ug/L	30-100	50	0-350	50	4-160	40

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controlling the length of contact time with the rocks. Chemical processes, such as ion filtration (Wood, 1976), or ion exchange may also have been significant controls on water quality.

Dissolved-solids concentration (designated as "residue dissolved" in Tables 76-80) in most samples were in the 200-600 mg/L range with maximum values about 1400 mg/L. Water in the middle and deep aquifers was the most highly mineralized, reflecting longer contact time with the rocks. The pH was normally 6.5-8.0 and also tended to be higher with depth. Hardness was generally 150-300 mg/L (hard to very hard water). Total concentrations of some minor constituents were affected by sediment in the sample, as discussed above; relatively low values, obtained from relatively sediment-free samples, were more representative of dissolved concentrations. In all samples, even the total concentrations of some constituents were below the recommended limits for dissolved concentrations. These constituents, and their recommended limits, are: copper (1 mg/L), zinc (5 mg/L), and silver (0.05 mg/L).

Dissolved-solids concentration showed a linear relationship to specific conductance (Figure 76). From specific conductance, therefore, an estimated value for dissolved-solids concentration was obtainable where it was not determined as part of the analysis (for example, analyses of samples collected before November 1976, including all of those from C06 and most from M09). Ground water of much higher salinity than shown on Figure 76 was collected from some wells at M09 and J08 and is described later.

Descriptions of ground-water quality of individual study watersheds are given below.

1. Watershed C06

Water in the top aquifer was mostly of the calcium bicarbonate type; a plot of major ions for a sample from well W1-1 (Figure 77) provides an example. In some samples of water from the top aquifer, magnesium was a codominant cation and sulfate a codominant anion. Other analyses plotted in Figure 77 illustrate wide differences in water type in the middle and deep aquifers. As no systematic variation in water type was evident, local conditions (lithology and hydraulic conductivity) probably exerted significant controls on water quality.

Results of chemical analyses of ground-water samples from C06 are summarized in Table 76. Specific-conductance values indicate that dissolved-solids concentration in parts of the middle and deep aquifers (wells W9-2 and W8-3) exceeded the recommended limit of 500 mg/L. Concentrations of dissolved iron and manganese commonly exceeded recommended limits of 0.3 and 0.05 mg/L, respectively. Concentration of dissolved cyanide exceeded the recommended limit (0.01 mg/L) in one sample from W8-3.

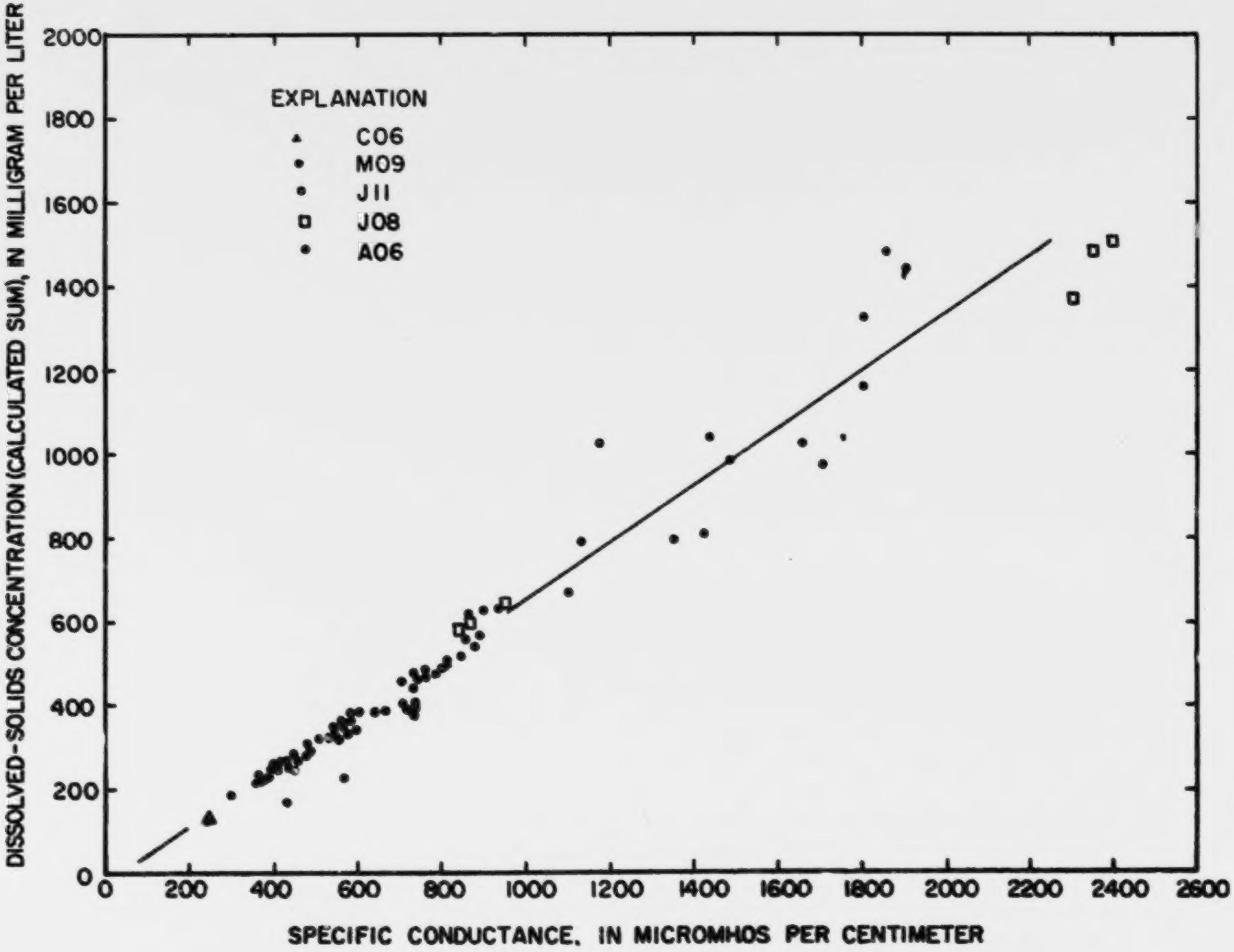


Figure 76. Graph of Dissolved-Solids Concentration Versus Specific Conductance

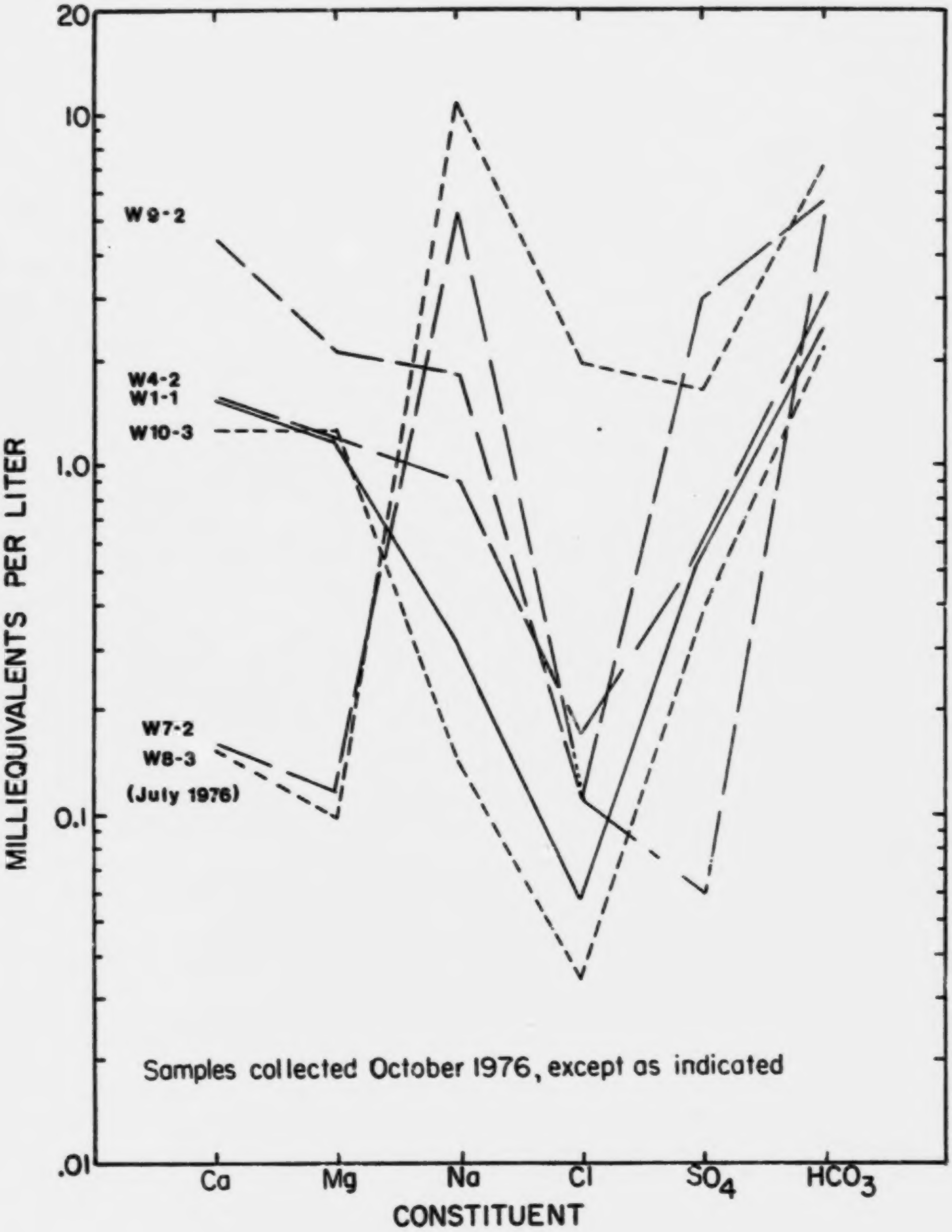


Figure 77. Concentrations of Major Ions in Ground-Water Samples for C06

2. Watershed M09

Water in the top aquifer was mostly of the calcium magnesium bicarbonate type; analysis of a sample from well W8-1 (Figure 78) was typical. Chemical composition of water in the middle aquifer showed a relationship to the flow system (Figure 79). In the upgradient area (W2-2), water type was similar to that in the top aquifer. Farther south toward the stream, sodium became the dominant cation (W5-2). The eastern part of the middle aquifer (W7-2) and the deep aquifer contained sodium chloride water.

The high mineralization of some of the ground water at M09 makes appropriate, for descriptive purposes, a reference to the following water-classification scheme given by Davis and DeWiest (1966):

Name	Concentrations of total dissolved solids, in milligrams per liter
Fresh water	0-1000
Brackish water	1000-10,000
Salty water	10,000-100,000
Brine	more than 100,000

Most of the sodium chloride water discussed above was brackish according to the above classification. The sample from well W4-3 was salty water. Ground-water quality in the deeper aquifers may have been affected by deep seated brines similar to those common in oil and gas fields.

Results of chemical analyses are summarized in Table 77. Dissolved solids concentration of much of the water in the middle and deep aquifers exceeded the recommended 500 mg/L limit. Chloride concentration was excessive (greater than 250 mg/L) in the eastern part of the middle aquifer and in the deep aquifer. Water in the top aquifer was very hard (greater than 180 mg/L hardness as $CaCO_3$). It was softer in parts of the deeper aquifers where sodium was the dominant cation. Dissolved iron exceeded the recommended limit (0.3 mg/L) in one sample (W11-2), and dissolved manganese was excessive (greater than 0.05 mg/L) in several samples. The recommended limit for cyanide concentration (0.01 mg/L) was exceeded in two samples from the middle aquifer and two from the deep aquifer.

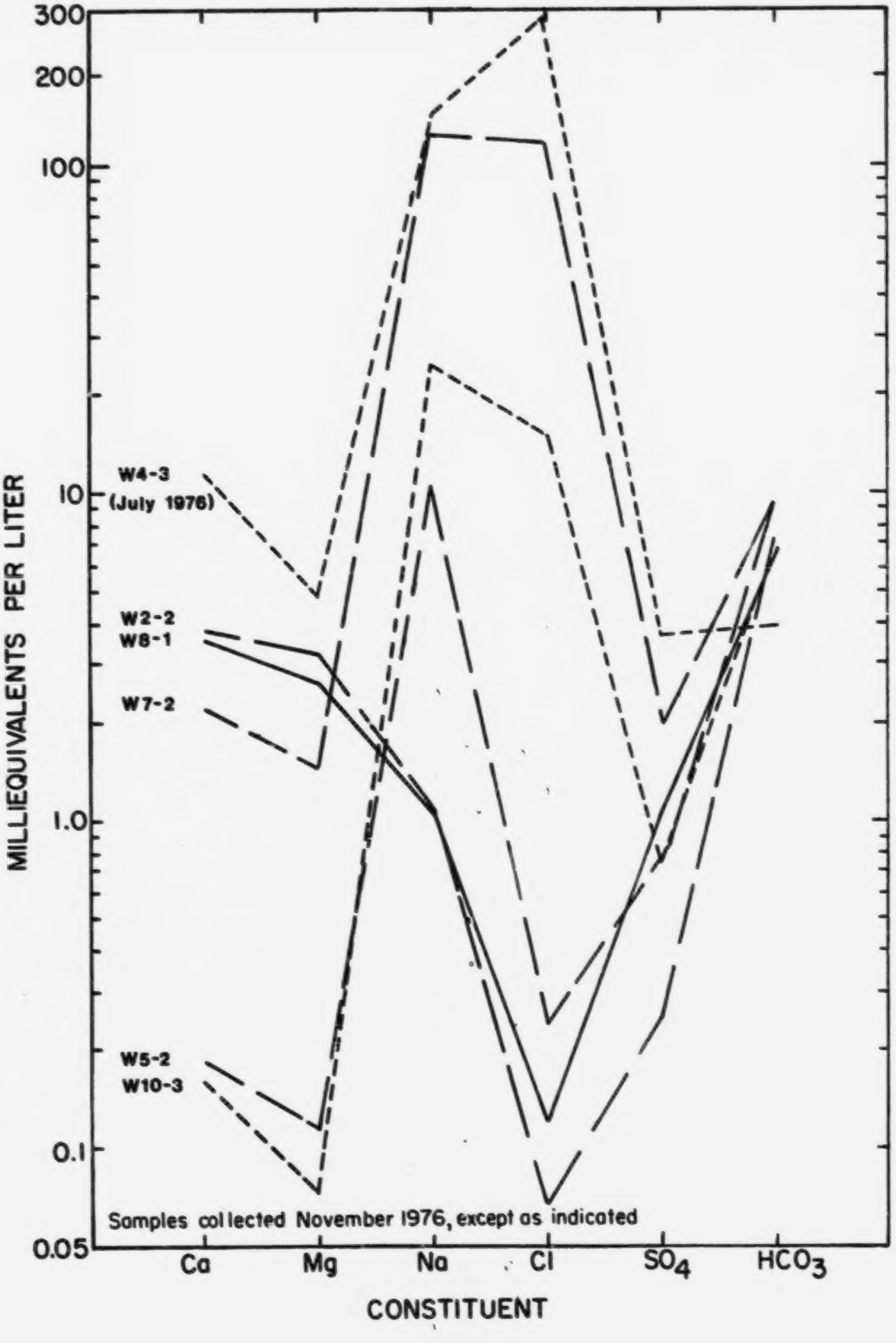


Figure 78. Concentrations of Major Ions in Ground-Water Samples for M09

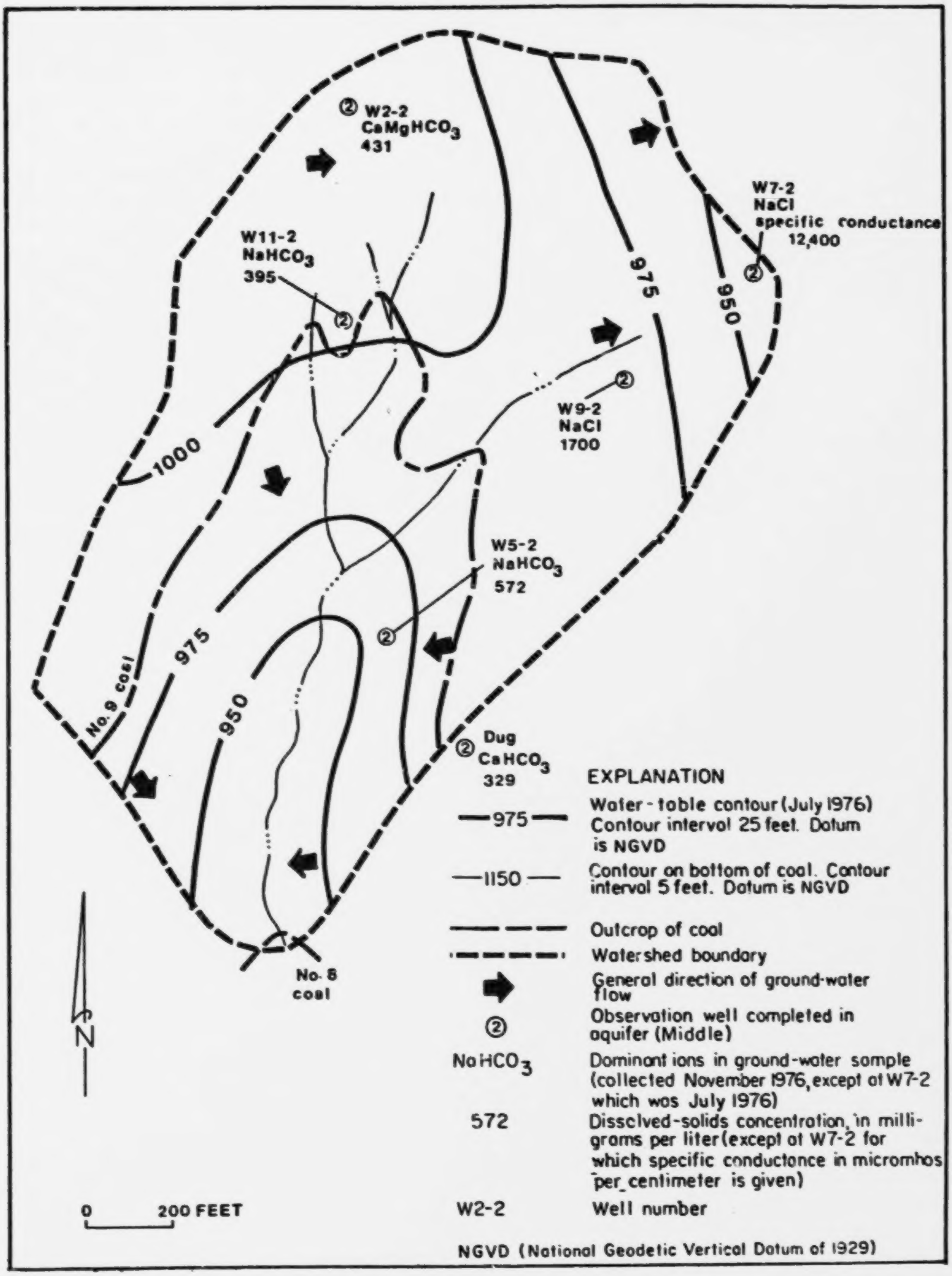

W2-2
CaMgHCO3
431
W11-2
NaHCO3
395
W7-2
NaCl
specific conductance
12,400
975
950
W9-2
NaCl
1700
1000
W5-2
NaHCO3
572
975
950
No. 9 coal
Dug
CaHCO3
329
No. 8 coal
N
0
200 FEET
EXPLANATION
975
Water-table contour (July 1976) Contour interval 25 feet. Datum is NGVD
1150
Contour on bottom of coal. Contour interval 5 feet. Datum is NGVD
Outcrop of coal
Watershed boundary
General direction of ground-water flow
②
Observation well completed in aquifer (Middle)
NaHCO3
Dominant ions in ground-water sample (collected November 1976, except at W7-2 which was July 1976)
572
Dissolved-solids concentration, in milligrams per liter (except at W7-2 for which specific conductance in micromhos per centimeter is given)
W2-2
Well number
NGVD (National Geodetic Vertical Datum of 1929)

Figure 79. Movement, Water Type, and Dissolved-Solids Concentration of Ground Water in the Middle Aquifer at M09

3. Watershed J11

The top aquifer at J11 contained water of the calcium bicarbonate and calcium sulfate types; an analyses from well W6-1 (Figure 80) was typical. All samples collected from the middle aquifer were bicarbonate waters, and sodium and calcium were the dominant cations; analyses from W7-2 and W8-2 (Figure 80) are examples. Figure 80 shows that the predominance of one major ion over another was not as extreme at J11 as at other study watersheds.

Results of chemical analyses are summarized in Table 78. Dissolved-solids concentration was below the recommended limit of 500 mg/L in all samples. Nearly all water in the top aquifer was very hard (greater than 180 mg/L hardness as $CaCO_3$); some of the water in the middle aquifer was softer. Although dissolved iron was not excessive, dissolved manganese concentration exceeded 0.05 mg/L in some parts of the top aquifer. Excessive cyanide concentrations (greater than 0.01 mg/L) have been detected in some samples from all wells in the top aquifer.

Premining ground-water quality data from J11, having been collected over a longer period than at C06 and M09, illustrated the nature of temporal water-quality variations. Two analyses from well W8-2 at different times (Figure 80) showed that dominant ions may change through time. Notable changes in concentrations of other selected parameters have been determined also (examples for both aquifers shown in Figure 81). Although the questionable representivity of some samples, mentioned previously, may partly explain the variations, the transient character of the hydrologic system was also a factor. For example, changing rate of recharge or leakage at a given place could effect a change in ground water quality if the water being added to the aquifer were chemically different from the aquifer water.

4. Watershed J08

Analyses of ground water from J08 indicated calcium sulfate water in the top aquifer, sodium bicarbonate water in the middle aquifer, and sodium chloride water in the deep aquifer (Figure 82).

Results of chemical analyses are summarized in Table 79. Water in the top aquifer was very hard, had dissolved-solids concentration exceeding the recommended limit of 500 mg/L, and sulfate concentration exceeding the recommended limit of 250 mg/L. Water in the middle aquifer was much softer, but slightly brackish and contained chloride concentrations exceeding the recommended limit of 250 mg/L. Water in the deep aquifer was brackish.

5. Watershed A06

Water in the top aquifer of the control watershed was of the calcium bicarbonate type. As in the other watersheds, water types in

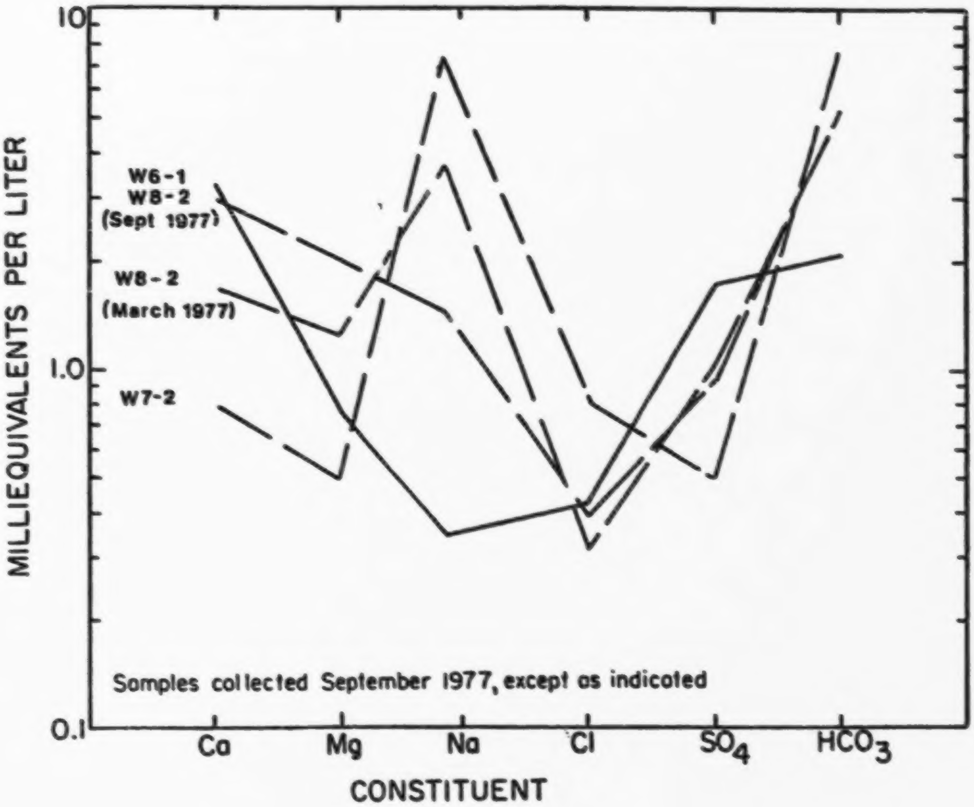


Figure 80. Concentrations of Major Ions in Ground-Water Samples from J11

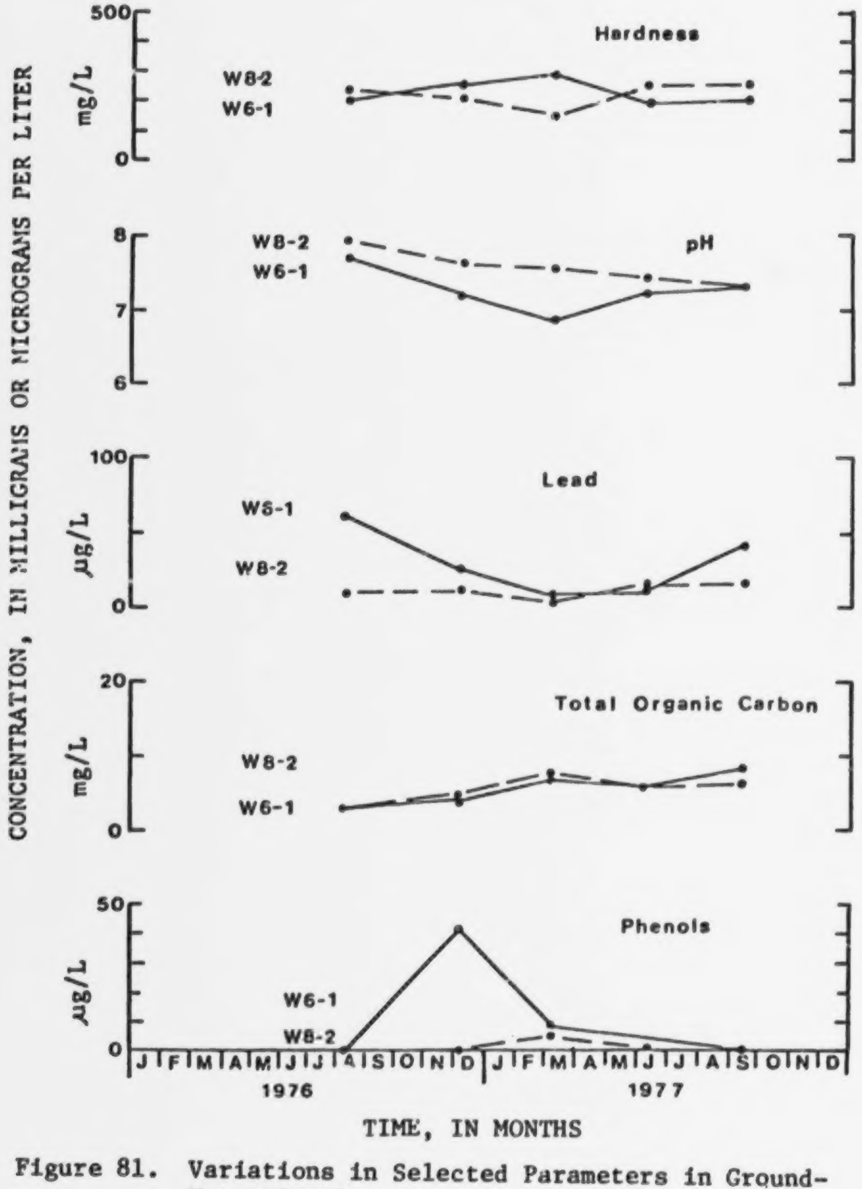


Figure 81. Variations in Selected Parameters in Ground-Water Samples from J11

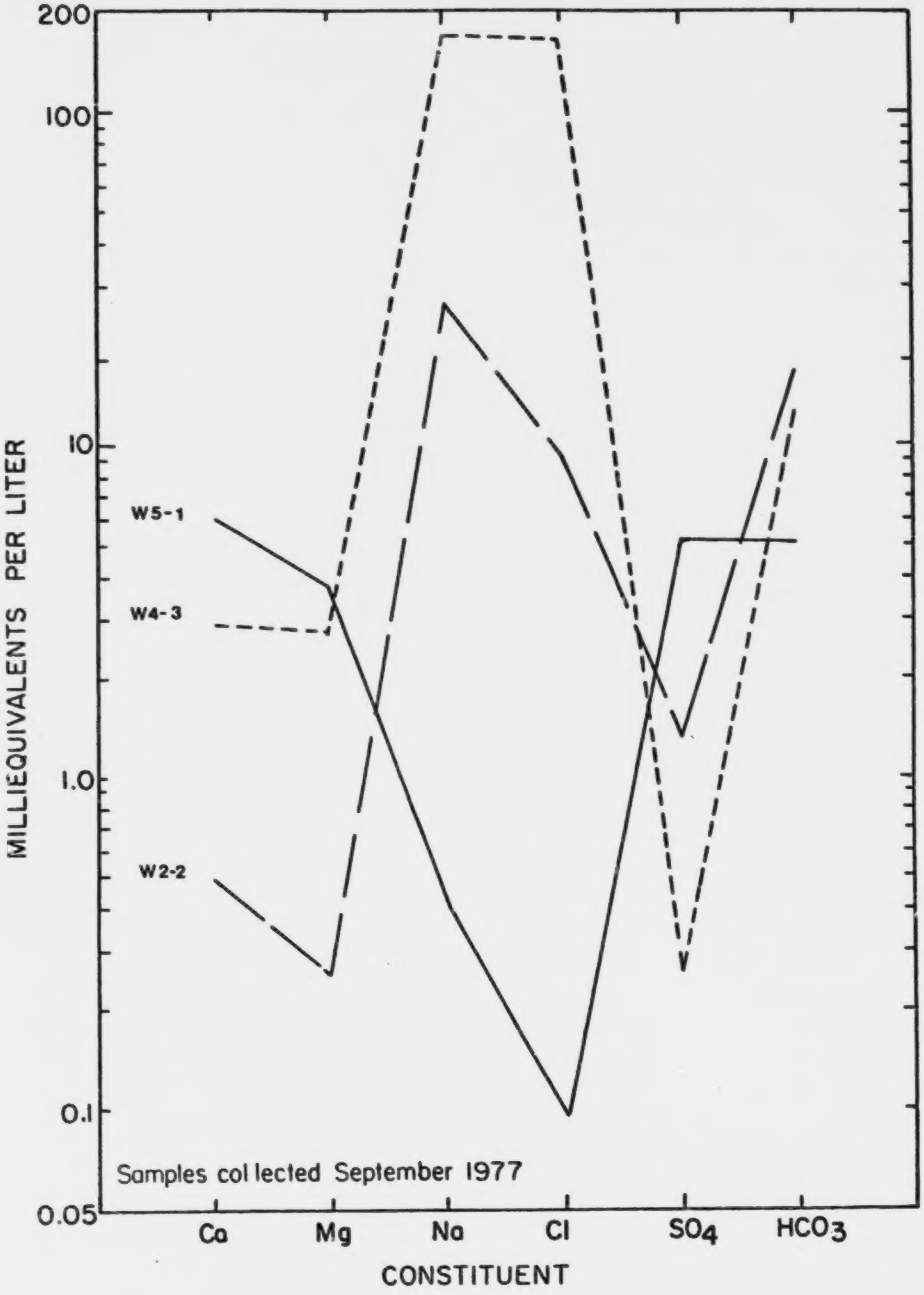


Figure 82. Concentrations of Major Ions in Ground-Water Samples from J08

deeper aquifers were more diverse. In the middle aquifer, calcium or sodium and sulfate or bicarbonate may each have predominated. The deep aquifer contained sodium bicarbonate and sodium sulfate waters.

Results of chemical analyses are summarized in Table 80. Dissolved-solids concentration exceeded 500 mg/L in samples from the middle aquifer (W4-2, W2,2), and in samples from both wells in the deep aquifer. Slightly brackish water was collected from wells W2-2, W9-3, and W10-3. Sulfate concentration exceeded 250 mg/L in water from wells W4-2, W2-2, and W10-3. Most water was hard to very hard, except from well W9-3, which yielded very soft water. Recommended limits of concentration for dissolved iron and manganese (0.3 and 0.05 mg/L, respectively) were commonly exceeded in all aquifers. Cyanide concentration exceeded 0.01 mg/L in one sample from W3-1 and one from W9-3.

VII. EROSION AND SEDIMENTATION

A. Watershed Sediment Yield

Some sediment yield data were obtained from Watersheds C06, M09, J11, and A06 in the premining condition. Samples taken consisted of discrete samples throughout the hydrograph, grab samples, and composite storm samples. Data from the grab samples are summarized in Table 81 and give the range of flows, the range of sediment concentration, the average of the samples taken, and whether they were taken on the rising or falling limb, or near the peak of the hydrograph.

1. Watershed C06

The range and average of the sediment data collected at the C06 site were the result of nine samples taken after the watershed had experienced some disturbance. The disturbance resulted from a network of access roads in the watershed for the movement of well drilling equipment. This network somewhat altered the runoff and sediment yield characteristics of the watershed, and the sediment yield would certainly exceed that expected for an unaltered state. The average suspended sediment concentration for four samples was 870 mg/l.

The C06 base-flow samples showed a wide range of sediment concentration which was probably due to some disturbance of the channels. The average base-flow suspended sediment concentration obtained from five samples was 247 mg/l.

2. Watershed M09

The M09 site showed a range in sediment concentration similar to C06; however, the maximum was associated with a flow more than three times as large as that at C06. Seven samples were analyzed. The average suspended sediment concentration for the two runoff samples was 1110 mg/l, while it was only 157 mg/l for the five base-flow samples. There was some disturbance in the watershed but not as extensive as in C06, because the watershed was much less forested and steep, and access to wells and construction sites was easier. A deep gully following the top of the southeast ridge of the watershed existed when the site was chosen. This gully, resulting from a gas well road, was reclaimed during the latter part of the premining period, but contributed somewhat to the sediment measured at the weir.

Two samples were collected at the M09 small watershed: one base-flow and one runoff. The sediment concentration in both cases was reasonably low, 75 and 84 mg/l, for an essentially grassed watershed.

Table 81. Summary of Sediment Data for Unmined Conditions (Grab Samples).

Site			Maximum		Minimum		Average**	Distribution of Samples In Hydrograph (Number)‡			
			SS*(mg/l)	Q+(cfs)	SS (mg/l)	Q (cfs)	SS (mg/l)	R	P	F	B
C06											
	Outlet	RO	1640	1.50	97	1.42	870	1		3	
		BF	978	.128	0	.001	247				5
M09											
	Outlet	RO	1980	5.295	241	.1495	1110		1	1	
		BF	415	.0524	0	.0045	157				5
	Small	RO	84	.193	84	.193	84			1	
		BF	75	.0021	75	.0021	75				1
J11											
	Outlet	RO	195	1.13	25	.0089	118	1	1	2	
		BF	72	.0121	13	.108	44				3
	Small	RO	2590	.0522	8	.0984	734	1	1	2	
		BF	18	.0121	18	.0121	18				1
A06											
	Outlet	RO	260	1.92	25	.428	144	2		4	
		BF	134	.0065	0	.0065	45				3
	Small		(No Samples Obtained)								

* - SS - Suspended solids
+ - Q - Flow rate associated with the SS value
** - Average of sediment samples
BF - Base-flow sample
RO - Runoff sample
‡ - R - Rising limb of hydrograph
- F - Falling limb of hydrograph
- P - Peak of hydrograph
- B - Base flow

The major sediment sources in the watershed, except for channels, were a dirt road at the top of the watershed and a bare area where a small access road left this dirt road to enter the watershed. These areas were considered minimal sources.

3. Watershed J11

The J11 outlet site showed, on the basis of four samples, a much smaller range of sediment concentration than the C06 or M09 sites with the maximum being 195 mg/l. The discharge associated with the maximum was similar to that at C06 which produced 1640 mg/l. The J11 site was relatively undisturbed with a good grass and forest cover. Sources of sediment were a secondary county road along one quarter of the watershed boundary, an access road across the upper section and a portion of a small corn field at the top of the watershed. The average sediment concentration for the four sampled events, including snowmelt and a thunderstorm, was 118 mg/l, as compared to an average of 44 mg/l for the three base-flow samples.

The small watershed experienced a much larger range in sediment concentration. The maximum of 2590 mg/l occurred during a thunderstorm in July, and the sediment source was probably the cornfield in the upper portion of the watershed. A concurrent outlet sample was not taken. The maximum observed sediment concentration was 324 times the minimum concentration. Maximum concentration was the result of a thunderstorm, and the minimum concentration of snowmelt. The average sediment concentration for the four sampled runoff events was 734 mg/l as compared to 18 mg/l for the one base-flow sample.

4. Watershed A06

Watershed A06, operated as a control watershed, had a heavy forest cover. The only major sediment sources were the gravel road at the top of the watershed, an old graveled access road to the weir along the upper reaches on the east side of the watershed, and three short side roads built for the access of well drilling equipment. The sediment concentrations were very similar to those obtained for the J11 site; the average for the six runoff events was 144 mg/l, as compared to 45 mg/l for the three base flows.

A composite vane sampler was installed at the A06 outlet. This sampler obtained one flow-weighted sample for an event. The four A06 composite samples (Table 82) showed an approximate four-fold range in sediment concentration.

Table 82. Summary of the A06 Composite Sediment Samples.

Total Samples	Maximum SS(mg/l)*	Maximum Qpk(cfs)+	Minimum SS(mg/l)	Minimum Qpk(cfs)	Average SS(mg/l)
4	262	4.32	58	3.94	150

*SS - Suspended solids
+Qpk- Peak flow of the event sampled

B. Erosion and Treatment Plots

The project proposal called for three sets of erosion and treatment plots to be installed on four different slopes and with different lengths on the slopes; one set on each of the disturbed overburdens associated with the Number 6, 9, and 11 coals. The erosion plots will consist of graded spoil material with a veneer of topsoil to the depth required by current regulations. One plot on each slope will have the original spoil exposed. The treatment plots (10 at each site) will consist of standard plots (72.6 ft. by 15 ft.) on a 9 percent slope, with treatments of differing depths of topsoil and mulching rates.

The erosion and treatment plots have been located on appropriate slopes outside the boundaries of, but near, Watersheds C06, M09, and J11. Construction has been initiated on the C06 plots.

The data from the plots will be used to develop criteria for diversion spacings, erodibility factors for the universal soil loss equation, and an erosion model for stripmine land.

Erosion and treatment plots will be discussed more fully in the Phase II report.

C. Sediment Ponds

Sediment ponds will be instrumented to monitor both inflow and outflow hydrographs and sediment graphs. These will be discussed in the Phase II report.

VIII. MODELING

A. Composite Model

1. Approach

This section of the report describes the general modeling approach. Subsequent sections document with mathematics and examples, some progress toward the development of a composite model. The effort to date in development of the composite model has been directed toward watershed hydrology modeling without water quality components. Water quality will later be incorporated into the model.

Several separate component models will be linked together to provide a composite model for simulation of surface and subsurface watershed hydrology. The models are as follows:

1. Ground-Water Model. This model will be a modification of the model developed by the USGS - "Documentation of Finite-Difference Model for Simulation of Three-Dimensional Ground-Water Flow," by Trescott and Larson (1976). It will receive recharge in the form of percolation from the unsaturated flow model (see Item 2), and will supply water table levels to define the lower boundary of the unsaturated zone as well as provide seepage effluent to the overland flow model (see Item 3).

2. Unsaturated Flow Model. This model will account for water movement in the unsaturated zone between the ground surface and the water table. To increase computational efficiency, this unsaturated model will be based on the one-dimensional flow equation. The three-dimensional watershed will be subdivided into prisms within which subsurface flows will be assumed to be vertical. The one-dimensional vertical flow solution will be obtained for each prismatic element within the watershed, or solutions at some of these prismatic elements will be obtained by interpolation from one-dimensional solutions covering the range of depths and conditions in existence.

3. Overland Flow Model. This model will numerically solve the kinematic wave equations to describe the manner in which precipitation excess and ground-water effluent is routed over the surface to the watershed outlet. The tractive forces from the velocity of overland flow will be important in determining surface erosion. The overland flow model will be based on a computer program developed by Rovey et al (1977), which describes the watershed surface by a cascade (logical flow sequence) of overland flow planes and channels.

4. Evapotranspiration Model. The evapotranspiration model will account for water removal by plant transpiration and surface evaporation. In practice it will be very closely associated with the unsaturated flow model and might be considered part of that model rather than as a separate model. It will consist of equations which determine the rate of evapotranspiration as a function of root penetration, meteorological elements, species of plants, stage of plant growth, and a soil water parameter.

Each of the separate component models will be based on fundamentally sound, physically-based formulations. Where partial differential equations are involved the associated initial boundary value problems will be solved numerically, because the nonlinear nature of the equations prevent solution in closed form.

The unsaturated model will receive precipitation data as input. Its basic functions will be to compute estimates of:

1. The infiltration capacity of the watershed.
2. The precipitation excess which becomes overland flow.
3. The movement of infiltrated water through the upper zone.
4. The time and amount of percolation into the water table, and thereby provide recharge to the ground-water model.
5. The soil water content and hydraulic pressure in the unsaturated zone at all times for computing water flow and evapotranspiration.

The time increment that can be used in numerically solving the differential equations for this unsaturated flow model will be larger, no doubt, than the time increment needed for the overland flow model, but shorter than the time increment of the ground-water model. The depth of each prismatic element of unsaturated flow will equal the difference between watershed surface elevation at that point and the ground-water table at that point. Thus, the heights of individual unsaturated prismatic elements will depend upon the solutions obtained from the ground-water model. In turn, the flow through the unsaturated zone is needed by the ground-water model for its solution. Likewise, the overland flow model will require data from both the unsaturated flow and ground-water models. As input for each new time step, this needed information will be passed between the separate component models.

Many alternate approaches to modeling are available. For example, the ground-water and unsaturated flow zones might all be included in a single mathematical formulation. As part of the numerical solution of this problem, the position of the water table would be provided.

Past efforts using the entire saturated-unsaturated region include the following: Rubin (1968), Taylor and Luthin (1969), Jeppson (1969), and Freeze (1971).

Several considerations led to the decision to use separate component models coupled together to form a composite model. These are as follows:

1. The existing ground-water model is adapted to use field data from well log records, and has been successfully used in some preliminary analyses of study watersheds early in the research program.

2. Considerably greater computational efficiencies are possible through the separate model approach, because time steps might be made compatible to the time scale of occurrence, and simplifications in formulation are possible that cannot occur in a single model.

3. Since overland flow is governed by differential equations of different types, they would be separate anyway.

To visualize how hydrology within and on a watershed will be simulated by numerical computer solutions, consider a typical watershed as depicted in Figure 83. The premined watersheds considered in this study had perched water tables above the clay layers underlying each of two coal beds. Recharge for the upper water table came from precipitation on the surface. The lower aquifer was recharged by leakage, probably by localized percolation along the outcrop of the upper aquifer, and by precipitation on the exposed surface between the two aquifers. Thus, there were two water tables and two separate unsaturated zones in the premined watersheds.

Figure 83 depicts the greater detail in the upper unsaturated-saturated zones. The unsaturated zone is divided into prismatic elements for numerical simulation. Unsaturated water movement in each such element will be considered to be one-dimensional in the vertical direction. Lateral movement will be restricted to the surface and ground-water flows. Precipitation, q_r, as given by a histogram, or from snowmelt predictions, enters the surface of each element. Evapotranspiration, denoted as E-T in Figure 83, will remove soil water as controlled by plant, soil water, and weather conditions. Therefore, each prismatic element will contain a time-dependent volume of water that is distributed through the length of the element according to the solution of the unsaturated flow equation. As this water moves downward, some will eventually move into the saturated zone. This so-called percolation is denoted by q_d in Figure 83 and constitutes recharge to ground water. The amount of this recharge, along with the discharge capabilities of the ground-water aquifer, will dictate the level to which the water table will rise at the centerline of each prismatic element.

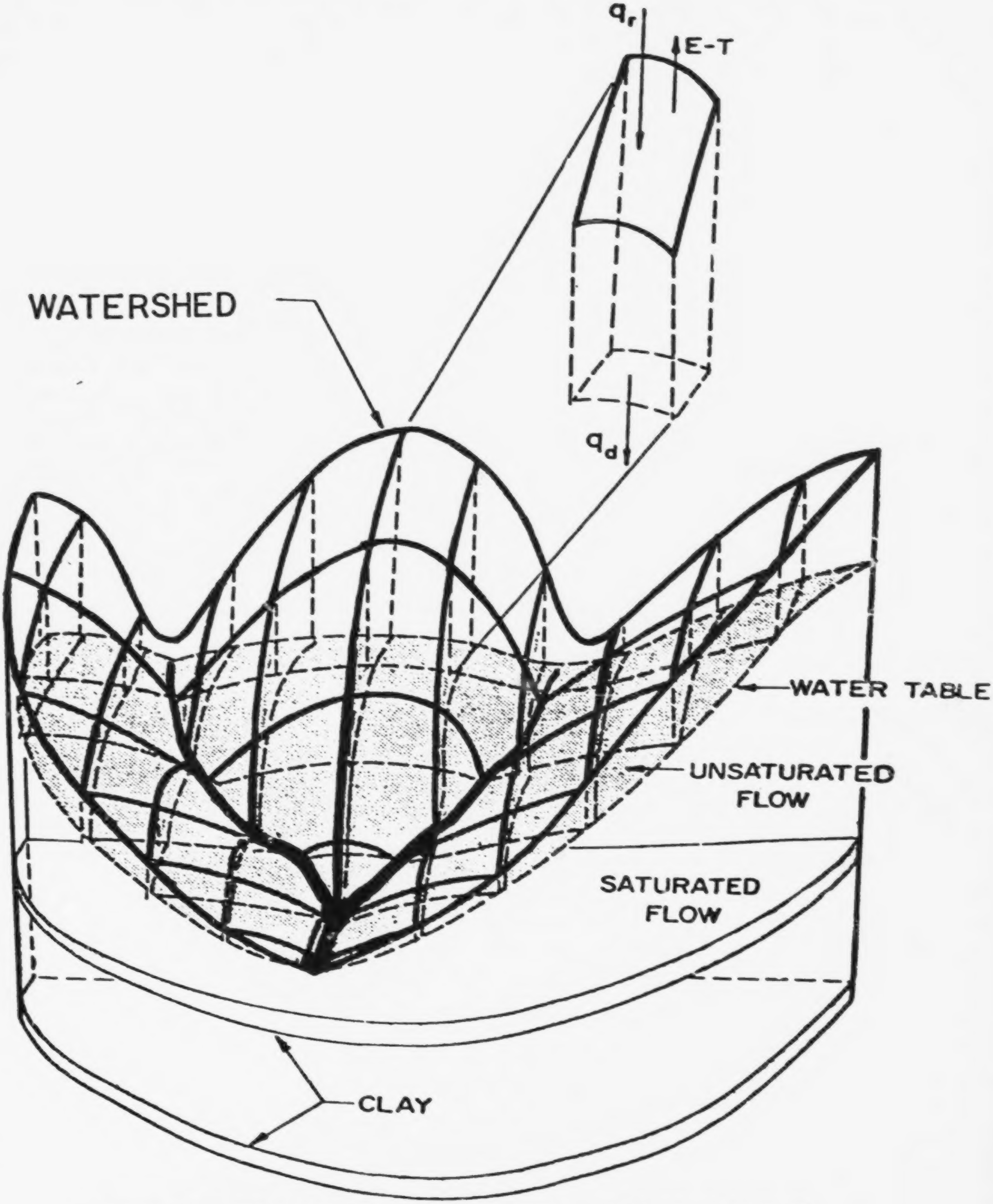

q_r
E-T
WATERSHED
q_d
WATER TABLE
UNSATURATED FLOW
SATURATED FLOW
CLAY

Figure 83 - Schematic of Watershed for Numerical Simulation of Hydrologic Response of Flow Processes

The mechanism for coupling the ground-water and unsaturated component models will be to pass the needed information back and forth after individual time steps have been completed and not during the individual solutions of a time step. Thus, it will be possible, for the unsaturated model to use a smaller time increment than the ground-water model. Likewise, data will be passed back and forth to the overland flow model at the completion of individual time increments. The time increment of the overland flow model might also be independent of the other time increments. If time increments are different, however, they will need to be multiples of each other.

2. Coupling Component Models

A major future effort will be required to develop the heart of the composite model, that is, the program that couples the component models and directs and coordinates their individual activities so that complete and accurate simulation of total watershed hydrology is achieved. This driving and coordinating program will require a minimum of data to define the watershed being simulated (its physical and hydrologic characteristics), the characteristics of the simulation desired, and the type or form and extent of solution results wanted. It will:

1. Define the outline of the watershed from limited, easily provided data.

2. Divide the watershed into appropriate prismatic elements for the unsaturated model.

3. Define the height of each element from limited data easily obtained from a contour map and water table elevations.

4. Direct the obtaining of unsaturated solutions for some prismatic elements covering the ranges of conditions required within the watershed, and then by proper interpolation of these solutions determine water movement characteristics in the remaining elements.

5. Define the finite difference grid for use by the ground-water model, and the transmissivities at each grid element.

6. Define recharge and discharge, constant head elements, and other boundary conditions for the ground-water model.

7. Coordinate the solutions of the separate models and pass appropriate data between models when these data are needed as input.

8. Control and direct the simulation output as requested by the user.

The programming has been completed to accomplish items 1 and 2 above. The techniques for accomplishing these tasks are described in the next section. Progress has been made on Item 4, and the remaining three items are planned for the future.

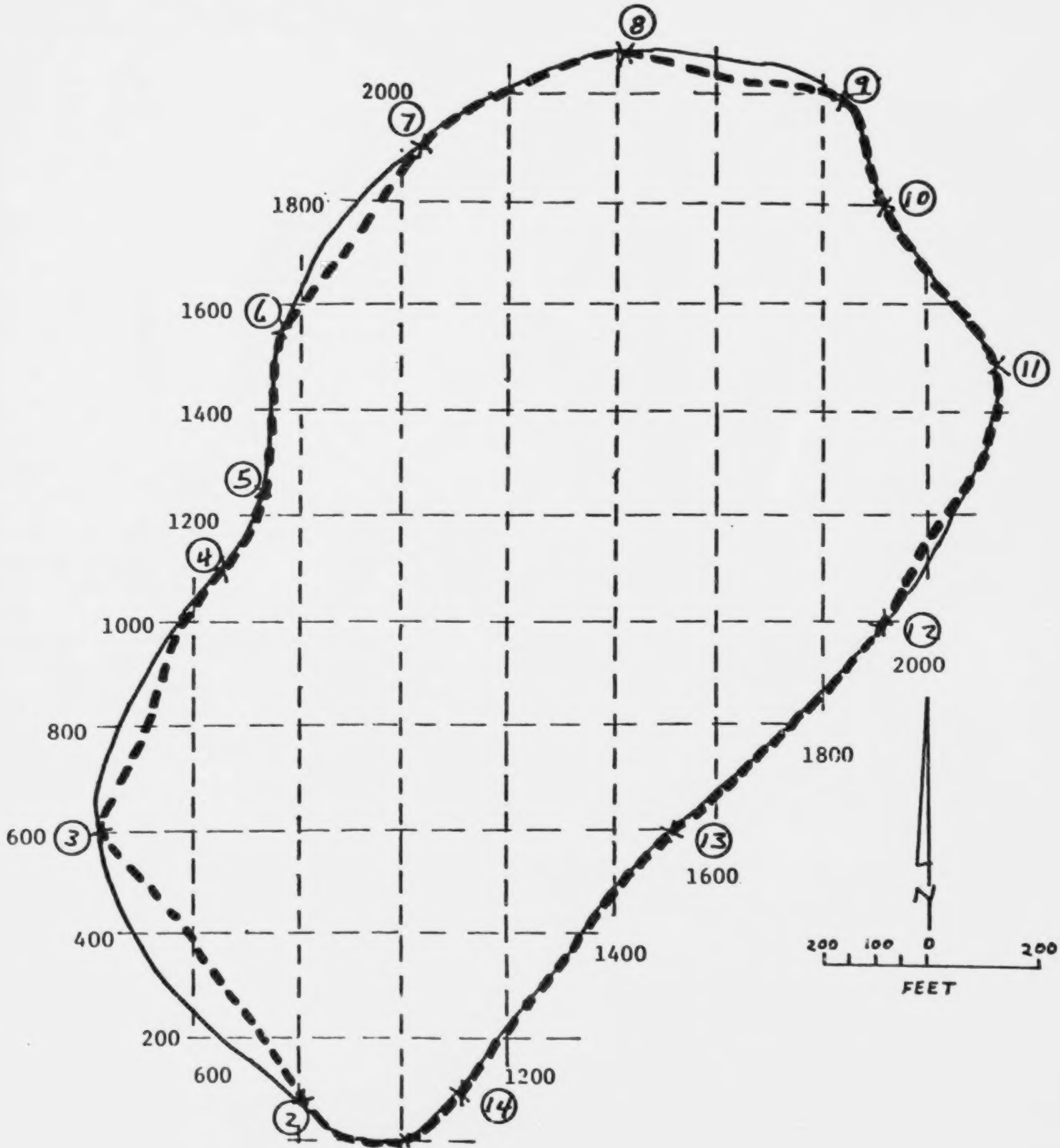
3. Defining Watershed Geometry

The shape of the watershed is defined by giving x and y coordinates around the periphery of the watershed. The coordinates can be selected arbitrarily, but to accurately define the actual watershed shape, they should be selected at major changes in the direction of the periphery. These given coordinates are fitted by splines under tension. A description of splines under tension, and how these coordinates are fitted, is described in the next section.

A grid network consisting of vertical and horizontal lines is superimposed over the watershed map. The spacing of the lines in the x-direction (i.e. between vertical lines) is constant and equal to Δx. The spacing of the lines in the y-direction (i.e. between horizontal lines) is constant and equal to Δy. The positioning of both sets of lines (Δx and Δy as some multiple of 10) is made so that the left vertical and bottom horizontal lines are as close as possible to the minimum value of x and y, but also within the watershed or possibly on its boundary. The computer program determines the grid network from input data consisting of Δx, Δy, and the x and y coordinates given around the periphery of the watershed.

In determining the grid network the intersection of each horizontal grid line along each of the vertical grid lines is obtained. Also, the intersections of the vertical grid lines are determined along each horizontal grid line. The intersections of the grid lines are thus actually determined twice, and either determination might be used to define all intersections within the watershed. However, the intersections of the grid lines with the boundaries of the watershed are determined, in general, only once. The intersections of the vertical grid lines with the boundaries are the first value and the last value in each array of y coordinates for that vertical grid line. Likewise, the first and last number in each array of intersections along each of the horizontal grid lines gives the intersections of these lines with the watershed boundaries. Therefore, the length of all irregular spaces between the grid lines and the boundaries of the watershed can be determined as the difference between the first and second, or last and second from the last values in the arrays of numbers representing y or x coordinates along the grid lines.

Watershed M09, shown in Figure 84, will be used to illustrate the above. First, 14 points are selected around the periphery of the watershed. The first of these was taken at the mouth of the watershed, though this was not necessary. It was necessary that these points be ordered consecutively in a clockwise direction around the periphery.



⑧
2000
⑦
⑨
1800
⑩
1600
⑥
1400
⑪
⑤
1200
④
1000
⑫
2000
800
1800
600
③
⑬
1600
400
1400
200
100
0
200
FEET
N
200
600
1200
⑭
②
800
①
1000

Figure 84. Outline of Watershed M09 Defined by Spline Functions (Solid Line) Compared with Original Watershed Outline (Dashed Line)

The beginning point was not duplicated as the last point to close the watershed, rather this closing occurred internally within the fitting algorithm. The x and y coordinates around the periphery are given in Table 83.

Table 83. Coordinates x and y on the Periphery of Watershed M09, in Feet.

Point No.	1	2	3	4	5	6	7
x-coord.	1000	800	410	640	720	750	1020
y-coord.	0	80	600	1100	1250	1550	1900
Point No.	**8**	**9**	**10**	**11**	**12**	**13**	**14**
x-coord.	1400	1820	1900	2120	1900	1500	1100
y-coord.	2080	2000	1800	1500	1000	600	100

The shape of the watershed (solid line), Figure 83, was defined by spline functions with a tension factor $\sigma=1$, and angles of 180^o and 45^o, respectively, for the line joining at point 1. On this figure the original watershed M09 boundary (dashed line) has been superimposed. From the actual shape, one can see which additional coordinate points would result in a more accurate fit.

For example, adding a point approximately midway between points 2 and 3 with coordinates (650,300) would eliminate the deviation in this region. Also, an additional point between 3 and 4 was needed with coordinates (520,850).

The computed x and y coordinate values from the splines under tension fit are given in Table 84.

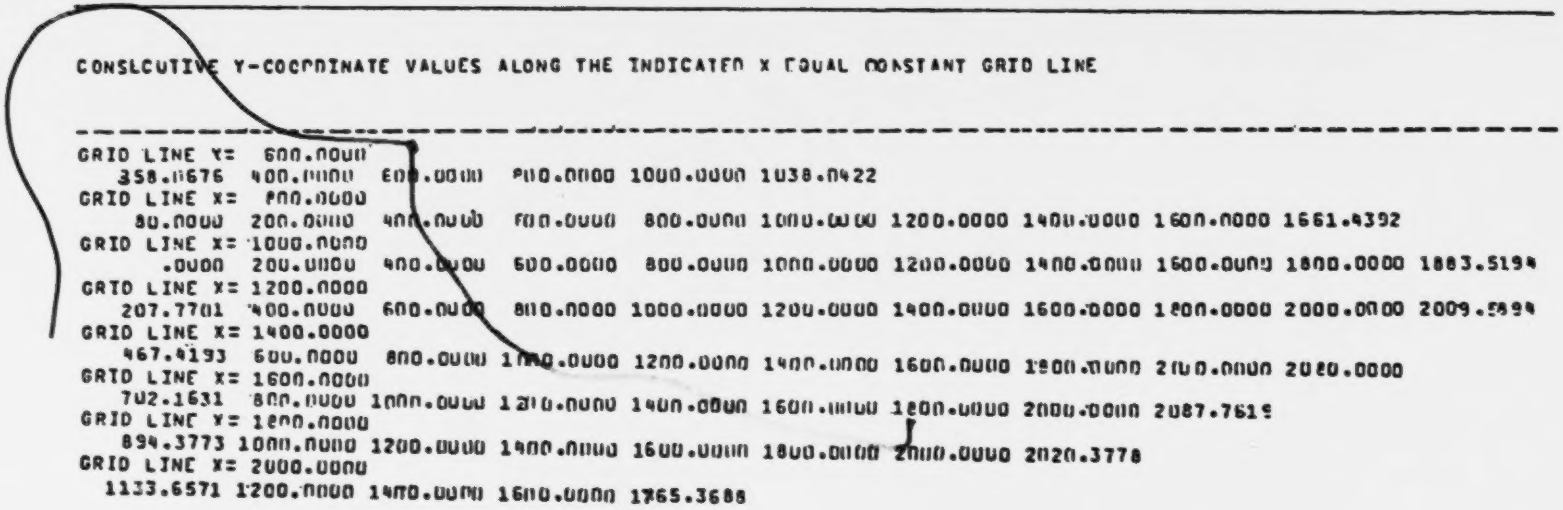
Table 84. Watershed Boundary Defining Coordinates Generated by Spline Functions from Given Coordinates (Table 83), in Feet.

x-coord.	1000	823.7	661.9	523.1	430.4	415.4	479.9
y-coord.	0	64.2	189.3	337.8	500.4	670.8	844.3
x-coord.	583.7	690.3	736.0	749.8	831.8	967.1	1121.2
y-coord.	1015.7	1180.8	1359.3	1548.9	1716.5	1857.3	1969.7
x-coord.	1289.7	1487.8	1693.8	1834.2	1901.1	2021.2	2122.0
y-coord.	2050.3	2092.0	2077.8	1977.2	1797.8	1640.1	1493.8
x-coord.	216.1	204.7	1879.4	1734.6	1597.7	1486.2	1403.9
y-coord.	1325.1	1146.4	977.0	829.9	700.3	583.9	472.3
x-coord.	1310.8	1155.6					
y-coord.	341.0	158.4					

Specifying that $\Delta x = \Delta y = 200$ ft., the computer computations produced the y intersections along each of the vertical (x equal constant) grid lines as given in Table 85. The x intersections along each of the horizontal (y equal constant) grid lines are given in Table 86. In both Tables 85 and 86, on most of the grid lines, intervals shorter than the regular $\Delta x = \Delta y = 200$ ft. exist at the ends of the lines. Only when an intersection falls exactly on the boundary do these shorter intervals not occur.

The area of each element was also computed (Table 87). The area of an element is defined as the area closestto an intersection of a given vertical and a given horizontal grid line. From this definition, the boundaries of the areas exist midway between grid lines or between grid lines and neighboring segments of the watershed boundary, whichever the case may be. For any grid intersection sufficiently within the watershed that no boundary is within a distance of Δx in the horizontal direction or Δy in the vertical direction, the area is Δx times Δy. For those grid intersections closer than this to the boundaries, the areas are computed by the trapezoidal rule.

Table 85. Computer-Generated Table of y-Coordinate Values Along Each of the Vertical (x Equal Constant) Grid Lines.



```
CONSECUTIVE Y-COORDINATE VALUES ALONG THE INDICATED X EQUAL CONSTANT GRID LINE

--------------------------------------------------------------------------------
GRID LINE X=  600.0000
   358.0676  400.0000  600.0000  800.0000 1000.0000 1038.0422
GRID LINE X=  800.0000
    80.0000  200.0000  400.0000  600.0000  800.0000 1000.0000 1200.0000 1400.0000 1600.0000 1661.4392
GRID LINE X= 1000.0000
      .0000  200.0000  400.0000  600.0000  800.0000 1000.0000 1200.0000 1400.0000 1600.0000 1800.0000 1883.5194
GRID LINE X= 1200.0000
   207.7701  400.0000  600.0000  800.0000 1000.0000 1200.0000 1400.0000 1600.0000 1800.0000 2000.0000 2009.5894
GRID LINE X= 1400.0000
   467.4193  600.0000  800.0000 1000.0000 1200.0000 1400.0000 1600.0000 1800.0000 2000.0000 2080.0000
GRID LINE X= 1600.0000
   702.1631  800.0000 1000.0000 1200.0000 1400.0000 1600.0000 1800.0000 2000.0000 2087.7619
GRID LINE X= 1800.0000
   894.3773 1000.0000 1200.0000 1400.0000 1600.0000 1800.0000 2000.0000 2020.3778
GRID LINE X= 2000.0000
  1133.6571 1200.0000 1400.0000 1600.0000 1765.3688
```

Table 86. Computer-Generated Table of x-Coordinates Values Along Each of the Horizontal (y Equal Constant) Grid Lines.

```
CONSECUTIVE X-COORDINATE VALUES ALONG THE INDICATED Y EQUAL CONSTANT GRID LINE

-----------------------------------------------------------------------------------
GRID LINE Y=      .0000
   999.4106
GRID LINE Y=  200.0000
   658.0203  800.0000 1000.0000 1193.8410
GRID LINE Y=  400.0000
   599.4759  600.0000  800.0000 1000.0000 1200.0000 1353.1371
GRID LINE Y=  600.0000
   410.0000  600.0000  800.0000 1000.0000 1200.0000 1400.0000 1500.0000
GRID LINE Y=  800.0000
   462.3897  600.0000  800.0000 1000.0000 1200.0000 1400.0000 1600.0000 1702.2776
GRID LINE Y= 1000.0000
   574.9980  600.0000  800.0000 1000.0000 1200.0000 1400.0000 1600.0000 1800.0000 1900.0000
GRID LINE Y= 1200.0000
   636.4651  800.0000 1000.0000 1200.0000 1400.0000 1600.0000 1800.0000 2000.0000 2041.1191
GRID LINE Y= 1400.0000
   740.2194  800.0000 1000.0000 1200.0000 1400.0000 1600.0000 1800.0000 2000.0000 2120.5346
GRID LINE Y= 1600.0000
   765.7902  800.0000 1000.0000 1200.0000 1400.0000 1600.0000 1800.0000 2000.0000 2059.1026
GRID LINE Y= 1800.0000
   909.1042 1000.0000 1200.0000 1400.0000 1600.0000 1800.0000 1900.0000
GRID LINE Y= 2000.0000
  1131.5309 1200.0000 1400.0000 1600.0000 1800.0000 1820.0000
```

Table 87. Computer-Generated Table of Areas Associated with Grid Intersection Points

```
AREAS ALONG CONSECUTIVE X=CONSTANT LINES (NUMBER IN ( )  IS Y=CONSTANT GRID LINE)

-------------------------------------------------------------------------------------------------------
GRID LINE X=  600.0000
  42105. ( 400)  50000. ( 600)  47522. ( 800)  29756. (1000)
GRID LINE X=  800.0000
  48396. ( 200)  40000. ( 400)  40000. ( 600)  40000. ( 800)  40000. (1000)  40707. (1200)  31956. (1400)  34826. (1600)
GRID LINE X= 1000.0000
  20000. (   0)  59768. ( 200)  40000. ( 400)  40000. ( 600)  40000. ( 800)  40000. (1000)  40000. (1200)  40000. (1400)
  40000. (1600)  54123. (1800)
GRID LINE X= 1200.0000
  50627. ( 400)  40000. ( 600)  40000. ( 800)  40000. (1000)  40000. (1200)  40000. (1400)  40000. (1600)  40000. (1800)
  24830. (2000)
GRID LINE X= 1400.0000
  40000. ( 600)  40000. ( 800)  40000. (1000)  40000. (1200)  40000. (1400)  40000. (1600)  40000. (1800)  56000. (2000)
GRID LINE X= 1600.0000
  40456. ( 800)  40000. (1000)  40000. (1200)  40000. (1400)  40000. (1600)  40000. (1800)  57552. (2000)
GRID LINE X= 1800.0000
  40000. (1000)  40000. (1200)  40000. (1400)  40000. (1600)  40000. (1800)  26445. (2000)
GRID LINE X= 2000.0000
  28224. (1200)  44107. (1400)  42221. (1600)
```

In computing the areas, vertical grid lines are scanned one by one. At each intersection with a horizontal line, the end values for that horizontal grid line are examined. If the x-coordinate of the vertical line is equal to or greater than the first value on the horizontal line plus Δx, or less than the last value on this horizontal line minus Δx, and it is not the second point from the end, then it is a regular area equal to Δx times Δy. If any of these conditions are not satisfied, smaller sizes are computed.

a. Splines Under Tension

The shape of the watershed is determined by interpolation using splines under tension between boundary coordinates as described in the previous section. Splines under tension were implemented from an unpublished paper by Cline (1968). The spline under tension was introduced by Schweikert (1966) to imitate cubic splines (see Ahlberg et al, 1967) but avoid the spurious critical points induced by the latter. Splines under tension allow a smooth and accurate fit of local behavior. By varying a tension factor, the flexure of the fit can be varied. Sufficient tension will remove unwanted inflection points, and with a large tension factor an essentially straight line can be fitted between each consecutive pair of points.

A spline under tension can be developed from a differential equation. The differential equation involves values of the second derivative of the spline. Given a set of coordinates (x_i, y_i) and a constant tension factor σ, a real-valued function f is sought having two continuous derivatives such that,

$$f(x_i) = y_i \ , \quad i = 1, \text{---} \ n \qquad (1)$$

The quantity $f'' - \sigma^2 f$ is to vary linearly on each interval $\{x_i, x_{i+1}\}$ for $i = 1, \text{--}n-1$. That is, for $x_i \leq x \leq x_{i+1}$,

$$f''(x) - \sigma^2 f(x) = (f''(x_i) - \sigma^2 y_i) \frac{x_{i+1}-x}{\Delta x_i} + (f''(x_{i+1}) - \sigma^2 y_{i+1}) \frac{x-x_i}{\Delta x_i} \qquad (2)$$

in which $\Delta x_i = x_{i+1} - x_i$.

Solving Eq. 2 by satisfying the condition given by Eq. 1 results in,

$$f(x) = \{f''(x_i) \quad \sinh\left[\sigma(x_{i+1} - x)\right] + f''(x_{i+1})$$

$$\sinh\left[\sigma\ (x - x_i)\right]\}/[\sigma^2 \sinh(\sigma\ \Delta x_i)]$$

$$+ \left(y_i - \frac{f''\ (x_i)}{\sigma^2}\right)\left(\frac{(x_{i+1} - x)}{\Delta x_i}\right) + \left(y_{i+1} - \frac{f''\ (x_{i+1})}{\sigma^2}\right)\left(\frac{x - x_i}{\Delta x_i}\right) \qquad (3)$$

in which $x_i \leq x \leq x_{i+1}$.

Differentiating Eq. 3 with right- and left-handed derivatives equated, results in,

$$\left[\frac{1}{\Delta x_{i-1}} - \frac{\sigma}{\sinh\ (\sigma\Delta x_i)}\right] \frac{f''(x_{i-1})}{\sigma^2} + \left[\frac{\cosh(\sigma\Delta x_{i-1})}{\sinh\ (\sigma\Delta x_{i-1})}\right.$$

$$\left. - \frac{1}{\Delta x_{i-1}} + \frac{\sigma\ \cosh(\sigma\Delta x_i)}{\sinh(\sigma\Delta x_i)} - \frac{1}{\Delta x_i}\right] \frac{f''(x_i)}{\sigma^2} + \left[\frac{1}{\Delta x_i} - \frac{\sigma}{\sinh\ (\sigma\Delta x_i)}\right]$$

$$\frac{f''(x_{i+1})}{\sigma^2} = \frac{y_{i+1} - y_i}{\Delta x_i} - \frac{y_i - y_{i-1}}{\Delta x_{i-1}} \quad \text{for } i = 2, \text{---}\ n - 1. \qquad (4)$$

The ends of the spline can be given specified slopes. These specifications provide two additional conditions

$$f'(x_1) = y_1' \quad \text{and} \quad f'(x_n) = y_n' \qquad (5)$$

The conditions given by 5 can be utilized by again differentiating Eq. 3 at $x = x_1$ and $x = x_n$ and then equating to y_1' and y_n', respectively, to give

$$\left[\frac{\sigma\ \cosh(\sigma\Delta x_1)}{\sinh(\sigma\Delta x_1)} - \frac{1}{\Delta x_1}\right] \frac{f''(x_1)}{\sigma^2} + \left[\frac{1}{\Delta x_1} - \frac{\sigma}{\sinh(\sigma\Delta x_1)}\right] \frac{f''(x_2)}{\sigma^2}$$

$$= \frac{y_2 - y_1}{\Delta x_1} - y_1' \qquad (6)$$

and

$$\left[\frac{1}{\Delta x_{n-1}} - \frac{\sigma}{\sinh(\sigma\Delta x_{n-1})}\right]\frac{f''(x_{n-1})}{\sigma^2} + \left[\frac{\sigma\cosh(\sigma\Delta x_{n-1})}{\sinh\,(\sigma\Delta x_{n-1})} - \frac{1}{\Delta x_{n-1}}\right]\frac{f''(x_n)}{\sigma^2} = y_n' - \frac{y_n - y_{n-1}}{\Delta x_{n-1}}\ . \tag{7}$$

Equations 4, 6 and 7 are a tridiagonal system of linear equations for the unknowns $f''(x_i)/\sigma^2$ for $i = 1, 2$ -- n. Upon solving this system of equations the $f''(x_i)$ are known and can be used in Eq. 3 as the interpolating function.

If the problem is to fit an entire continuous curve through the coordinates (x_i, y_i), $i = 1, \ldots n$, then let $s_1 = 0$ and

$$s_i = s_{i-1} + \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} \tag{8}$$

for $i = 2$, -- n. It is now possible to fit two splines x and y as functions of the polygonal arc lengths with

$$x(s_i) = x_i$$

$$y(s_i) = y_i$$

These spline functions are identical to Eq. 3 with the exception that the arguments of the hyperbolic sines, as well as $x_{i+1} - x$ and $x - x_i$, are replaced by Δs's along the polygonal arc length. The equation for $f(y)$ is identical to that for $f(x)$ with the exception that y replaces x and a tridiagonal system must be solved for $f''(y_i)$.

B. Component Models

1. Unsaturated Flow Model

a. Introduction

Water movement in unsaturated soils is described on the basis of fundamental principles of conservation of mass and energy, whose mathematics produce partial differential equations. The resulting mathematical problem, called an initial boundary value problem, cannot be solved in closed form, in general, because the partial differential equation is nonlinear. Instead, a numerical approximation to the partial differential equations is usually solved. Prominant among the numerical methods being used are the methods of finite differences. In these methods, the dependent variable is discretized by imposing a grid (generally rectangular) within the region of the problem and then approximating the continuous function by a polynomial (generally second order) between some number of consecutive grid points. This discretization produces a system of simultaneous algebraic equations whose solution is a numerical approximation of the initial boundary value problem.

After deciding upon the general approach that was to be used in modeling surface and subsurface watershed hydrology, as described in a previous section, it was decided to develop a computer program to provide a finite difference solution to the unsaturated flow equation rather than to adapt some existing program to serve these needs. The mathematics and techniques used in the development of this unsaturated component model are described in the following sections.

b. Formulation of the Mathematical Initial Boundary Value Problem for the Unsaturated Flow Model

The differential equation which describes fluid movement through unsaturated soil is obtained by substituting Darcy's law, which is an expression of the energy principle, into the differential form of the conservation of mass equation. A form of the equation is,

$$\nabla(K\nabla h) = \eta \frac{\partial S}{\partial t} = \eta \frac{\partial S}{\partial P_h} \frac{\partial h}{\partial t} \tag{9}$$

in which h is the total hydraulic head, or fluid energy per unit weight of fluid, and herein will consist of the sum of the elevation head z and the pressure head $P_h = \frac{P}{\rho g}$, K is the hydraulic conductivity with dimensions of velocity, η is the soil porosity and is the volume of soil voids divided by the total volume, S is the water saturation and is defined as the volume of water divided by the volume of voids, t is time, and ∇ is the derivative vector operator, and, in cartesian coordinates,

$$\nabla \equiv \frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\vec{k} \cdot$$

In the expression for pressure head, P is water pressure in the pores of the soil, negative for unsaturated flow, ρ is water density, and g is acceleration due to gravity. The following assumptions are required for Eq. 1:

1. Darcy's Law is valid for unsaturated flow provided the hydraulic conductivity is expressed as an appropriate function of soil water saturation.

2. Gas flow which occurs as water fills or evacuates soil voids does so under such small gradients compared to the water flow that it can be ignored.

3. The fluid (water) is incompressible and, consequently, of constant density.

4. Solid particles of the soil do not move or consolidate and, consequently, η is constant for any soil layer.

5. On a macro scale, the functions which describe the flow and their derivatives are continuous so that the differential form of the continuity equation is valid.

In Eq. 9, h is considered the dependent variable. The pressure head (or pressure) might be introduced as the dependent variable from $h = P_h + z$, giving

$$\nabla(K\nabla P_h + K\vec{k}) = \eta \frac{\partial S}{\partial P_h} \frac{\partial P_h}{\partial t} \cdot \qquad (10)$$

By defining the soil water diffusivity as

$$D \equiv K\frac{\partial P_h}{\partial \theta} \qquad (11)$$

Eq. 9 can be modified so that the water content $\theta = \eta S$ is the dependent variable.

This third equation is

$$\nabla \cdot (D\nabla\theta) + \frac{\partial K}{\partial \theta}\frac{\partial \theta}{\partial z} = \frac{\partial \theta}{\partial t} \cdot \qquad (12)$$

While it is possible to show numerical advantages in solving Eq. 12 over Eqs. 9 or 10, or it is possible to enhance the numerical solution of Eq. 9 by the Kirchhoff transformation, Eq. 10 has been selected as the basic equation for which a finite difference solution will be obtained, because it interfaces well with the ground-water model. Because the unsaturated model is composed of vertical elements, each containing one-dimensional flow, Eq. 10 can be simplified to the following one dimensional-time dependent equation

$$\frac{\partial}{\partial z}\left[K_r\left(\frac{\partial P_h}{\partial z}+1\right)\right] = \frac{n}{K_o}\frac{\partial S}{\partial P_h}\frac{\partial P_h}{\partial t} \qquad (13)$$

in which the relative hydraulic conductivity $K_r = K/K_o$, K_o is the saturated hydraulic conductivity, and z is the vertical coordinate.

According to Eq. 13, the pressure head is a function of position in the profile and time. Since P_h is a function of z and t, it is useful to visualize unsaturated flow within each element of the watershed in the z-t plane of Figure 85. The origin of the coordinate z is the water table, and, because the level of the water table will differ at each element, the point z = o will be at a different absolute elevation for each prism throughout the watershed. The watershed surface constitutes the top, or right-most boundary in the z-t plane. On this watershed surface boundary a rainfall record provides a boundary condition consisting of a specified flux rate as a function of time. Another possible boundary condition for the watershed surface is a specified saturation S as a function of time. This latter condition occurs, for example, whenever the rainfall rate exceeds the intake capacity of the profile. The specified saturation may be unity. However, since all the air is seldom removed as water first enters the soil, even though the water may be ponded to a small depth on the surface, this specified surface saturation is more realistically given a value of 0.85 to 0.95.

The initial condition consists of values of the capillary pressure head at the beginning of the solution process. These are the values that must be assigned along the z-axis of Figure 85 when t = 0. Any number of possibilities exist, such as:

1. A hydrostatic equilibrium condition in which no water movement occurs. This hydrostatic equilibrium condition can be obtained from the fact that if no water movement exists, the gradient of hydraulic head, h, must be zero; i.e., the hydraulic head along the z-axis is a constant h_o. Therefore, $\partial P_h/\partial z = -1$ or

$$P_h(z,0) = P_h(0,0) - z = h_o - z. \qquad (14)$$

2. A condition in which the saturation or moisture content is constant. For constant saturation throughout the profile,

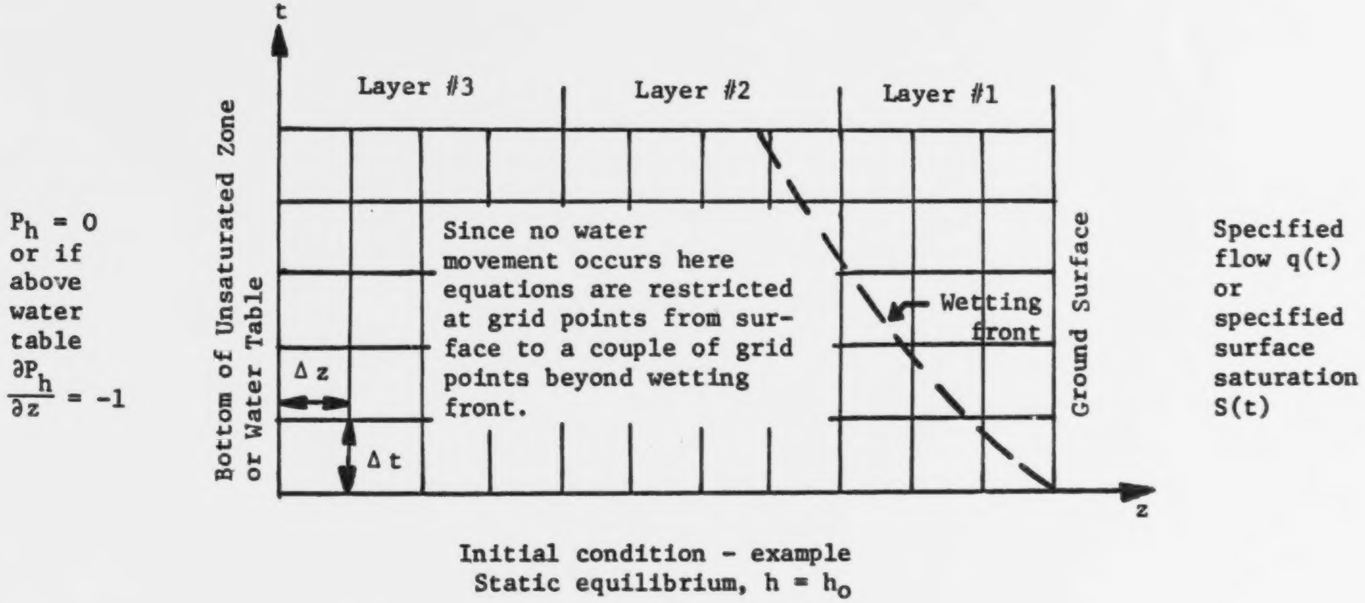

t
Layer #3
Layer #2
Layer #1
Bottom of Unsaturated Zone or Water Table
$P_h = 0$ or if above water table $\frac{\partial P_h}{\partial z} = -1$
Since no water movement occurs here equations are restricted at grid points from surface to a couple of grid points beyond wetting front.
Wetting front
Ground Surface
Specified flow q(t) or specified surface saturation S(t)
Δz
Δt
z
Initial condition - example
Static equilibrium, $h = h_o$

Figure 85. Unsaturated Water Movement in the z-t Plane

the initial condition comes from the relationship between saturation and pressure head which is discussed later.

3. A condition in which the hydraulic head or pressure head is given as a function of position z. An initial condition of this type would be given, for example, if the results from a previous simulation of unsaturated moisture movement are to be used for a new simulation that is to carry the solution to a new time.

4. A condition in which the saturation, or water content is given as a function of position z.

Condition No. 1 is shown in Figure 85 for illustrative purposes, even though any of the other three conditions may be used. For condition No. 1, no change will occur in the capillary pressure head until the influence from one of the boundaries reaches the point of interest within the profile. Such boundary influence can come from infiltration of rain on the surface. At depths beyond the wetting front of this infiltrating water no changes in P_h will occur. That is, P_h will remain as given by $P_h = h_o - z$. Changes in the value of P_h will be restricted to the space between the surface and the wetting front. Therefore, a computational efficiency can be achieved by only solving the equations from grid points up to and slightly beyond the wetting front. This efficiency has been built into the computer program and is noted in Figure 85.

The bottom boundary of the unsaturated zone will generally be taken at the water table. If this boundary is the water table, the pressure in the soil water will be atmospheric and, therefore, the condition is

$$P_h\ (0,t) = 0 \tag{15}$$

However, the computer program has been written to allow this boundary to be taken as any no-flux boundary until the soil at this depth reaches unit saturation. Thus, this boundary may be taken at the interface between a very well-drained sand or gravel layer and the topsoil as well as an impervious material, since the topsoil will not transmit water into a sand or gravel until it approaches unit saturation. After the soil at the zero boundary approaches unit saturation or the pressure head approaches zero, this boundary becomes a flow-through boundary, with P_h remaining constant and equal to zero.

c. Hydraulic Properties of Unsaturated Soils

The solution to any problem governed by the flow equation, Eq. 10, necessitates that relationships be established between the hydraulic conductivity, K, or the relative hydraulic conductivity, K_r, and the pressure, P_h, and also that pressure, P_h, be a known function of saturation S. One approach to defining these needed relationships is to use actual data obtained from laboratory or field tests. Another approach is to use equations containing parameters that can be varied to fit the properties of any given soil. A disadvantage of the first approach, of using actual soil data, is that a considerable data base is required, with a comparable increase in the amount of input data needed to use the computer program. The parametric equation approach has the disadvantage that no simple parametric equation has been presented that fits these needed relationships well for all soils and soil conditions. The phenomena of hysteresis exhibited by most soils between the desaturation and imbibition cycles further complicates the use of simple parametric equations for defining these hydraulic properties. In consideration of the limitations of both approaches and that detailed soil data are limited, costly, and difficult to obtain, it was decided to use the parametric equation approach. The equations selected are a modification of the Brooks-Corey equations (Brooks and Corey, 1964 and 1966) by the introduction of an additional parameter, a, which allows better fit of imbibition data. The equation selected to define the saturation-pressure relationship is

$$S = S_r + (1-S_r)\frac{a}{a + \left(\frac{P}{P_b}\right)^{\lambda}} \tag{16}$$

or

$$S_e = \frac{S-S_r}{1-S_r} = \frac{a}{a + \left(\frac{P}{P_b}\right)^{\lambda}} \tag{17}$$

in which S_r is the residual saturation and can be taken to be the small moisture content a soil will retain at very high capillary tensions (very small [negative] hydraulic pressure) when the hydraulic conductivity for practical purposes equals zero; P_b is the bubbling pressure, or air entry pressure, and represents the tension needed to first extract water from saturated soil; and λ is the pore size distribution exponent, a value small for soils with well graded grain sizes and large for soils composed of uniform grain sizes.

The relationship used for the relative hydraulic conductivity-pressure relationship is

$$K_r = \frac{a}{a + \left(\frac{P}{P_b}\right)^{2+3\lambda}} \tag{18}$$

The Brooks-Corey equations comparable to Eqs. 17 and 18 are:

$$S_e = \left(\frac{P_b}{P}\right)^{\lambda} \qquad \text{for } |P| \geq |P_b|$$
$$S_e = 1.0 \qquad \text{for } |P| < |P_b| \qquad (19)$$

and

$$K_r = \left(\frac{P_b}{P}\right)^{2+3\lambda} \qquad \text{for } |P| \geq |P_b|$$
$$K_r = 1.0 \qquad \text{for } |P| < |P_b| \qquad (20)$$

Eq. 20 can be obtained directly from Eq. 19 with the Burdine Theory (Burdine, 1952), or by integration of

$$K_r = S_e^{\,2} \, \frac{\int_{S_r}^{S_e} \frac{dS_e}{P^2}}{\int_{S_r}^{1} \frac{dS_e}{P^2}} \qquad (21)$$

Eqs. 19 and 20 both are straight lines on a log-log plot, whereas Eqs. 17 and 18 closely approximate a straight line on such a plot for small (negative) pressure values, but smoothly approach unity as P approaches zero. Thus, no discontinuity in the relationship exists as does in Eqs. 19 and 20 at $P = P_b$. These facts are illustrated in Figures 86, 87, and 88 in which the two parameters, a and λ , have been varied with $S_r = 0.15$ held constant, in generating the solid curves. The dashed curves show corresponding plots of Eqs. 11 and 12.

The solution of Eq. 13 requires derivatives of S and K_r with respect to the pressure head, P_h. Taking the derivatives of Eqs. 17 and 18 with respect to P_h produces the following:

$$\frac{\partial S}{\partial P_h} = (1-S_r)\,\frac{.5a\left(\frac{\lambda}{P_b{}^{\lambda}}\right)\left(P_{av}\right)^{\lambda-1}}{\left[a + \left(\frac{P_{av}}{P_b}\right)^{\lambda}\right]^2} \qquad (22)$$

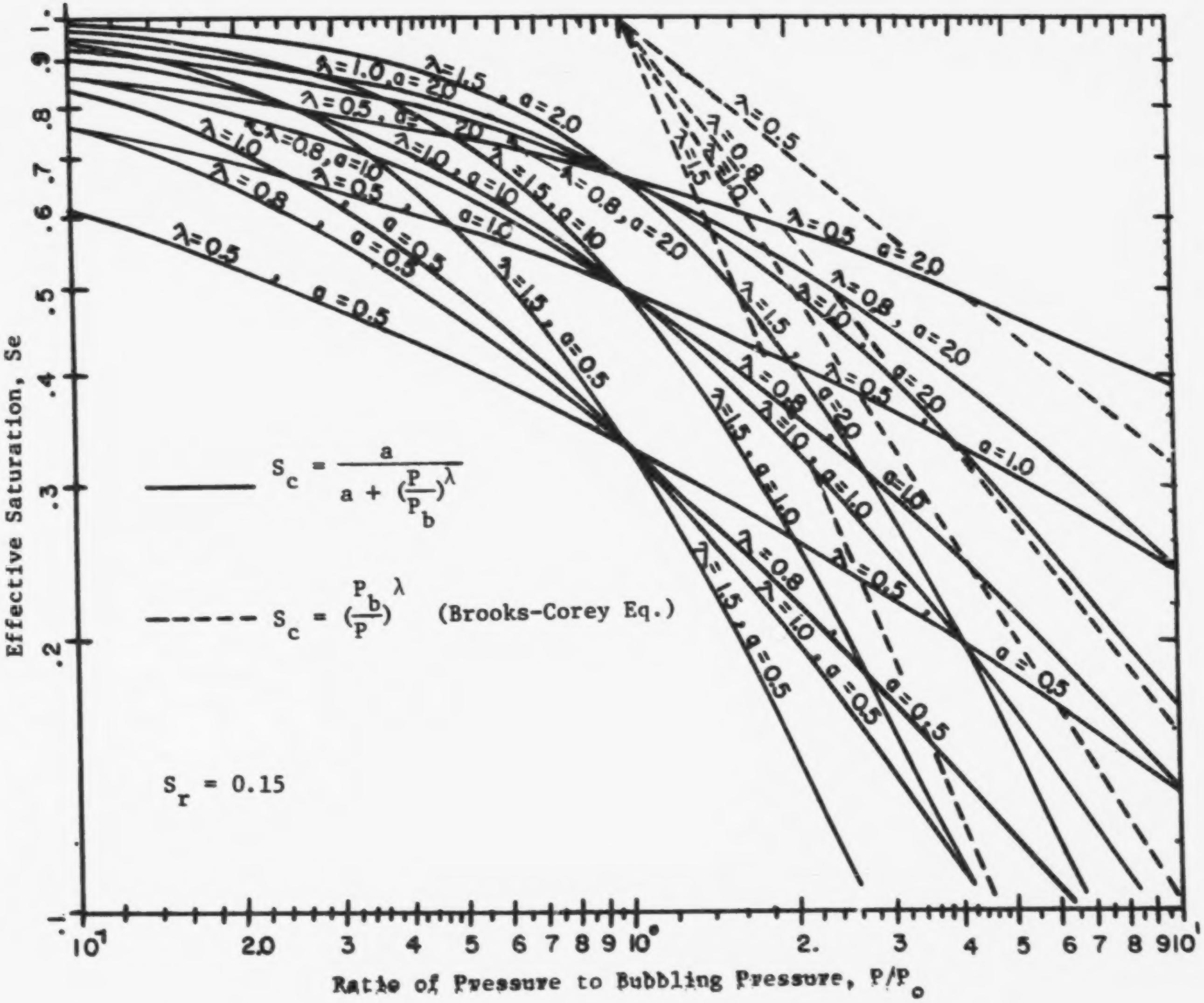


Figure 86. Effective Saturation-Capillary Pressure Curves for Several Values of the Pore Size Distribution Exponent λ and Parameter a

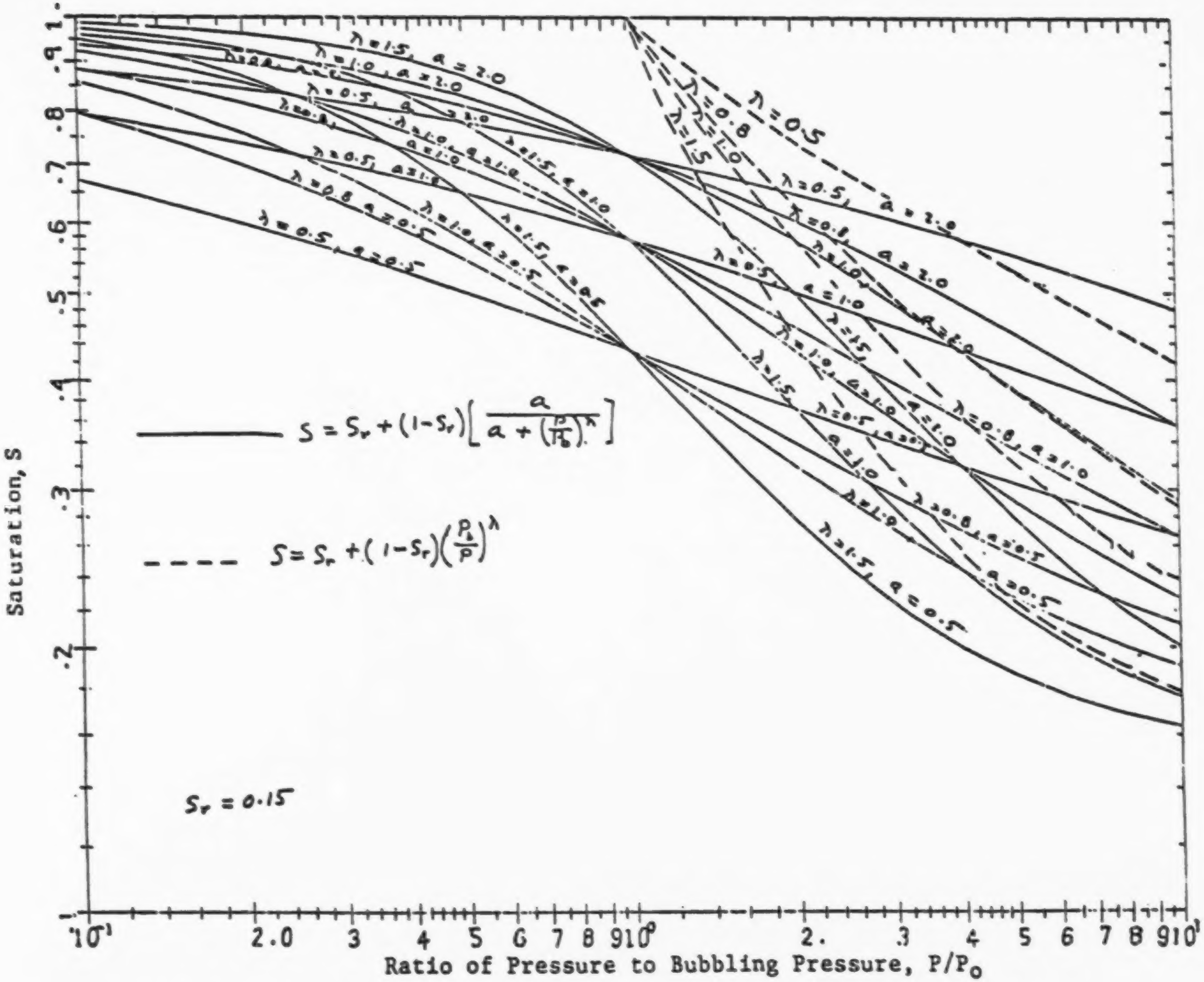


Figure 87. Saturation-Capillary Pressure Curves for Several Values of the Pore Size Distribution Exponent λ and Parameter a

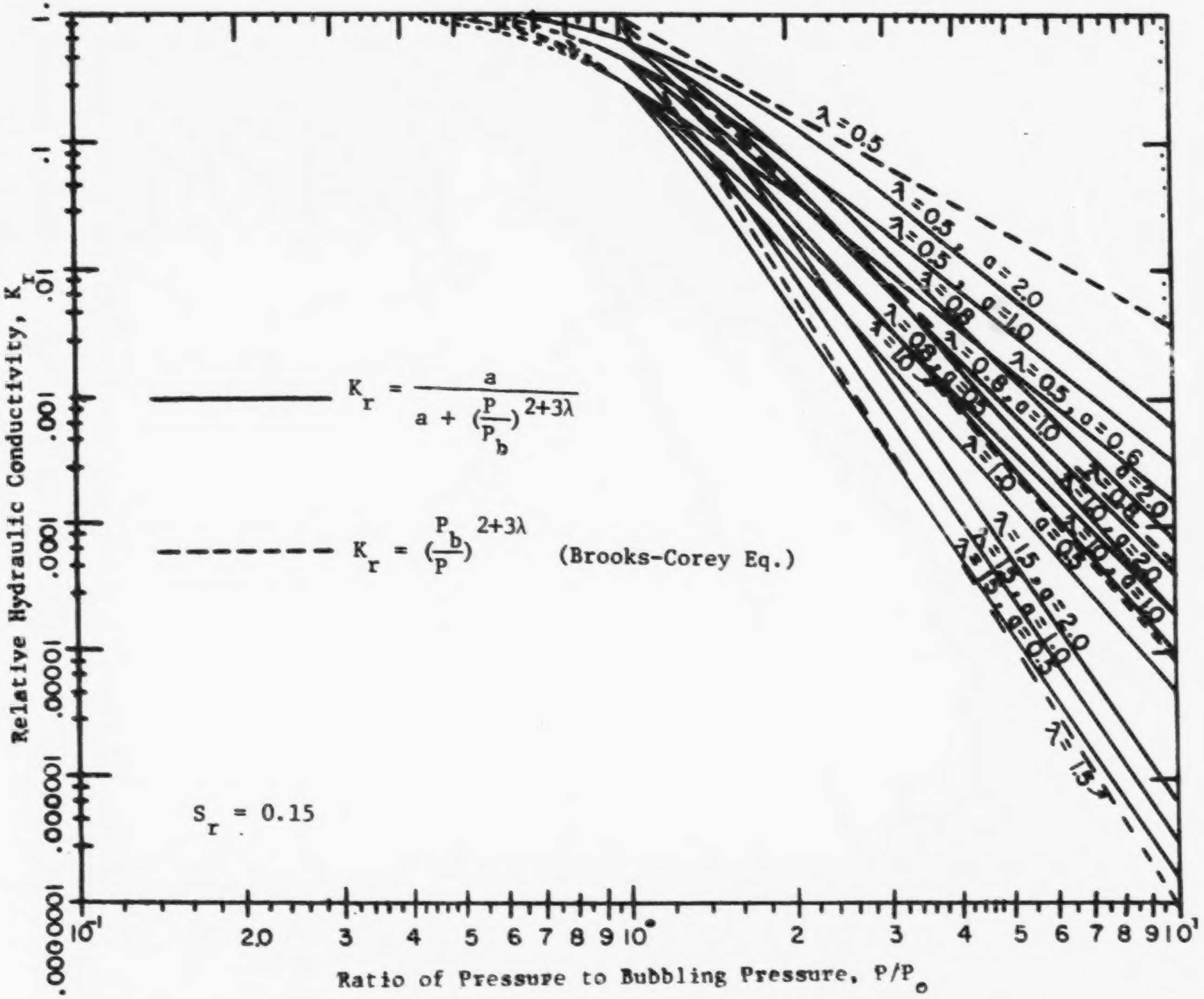


Figure 88. Relative Conductivity-Capillary Pressure Curves for Several Values of the Pore Size Distribution Exponent λ and Parameter a

and

$$\frac{\partial K_r}{\partial P_h} = - \frac{a\left(\frac{\varepsilon}{P_b^{\varepsilon}}\right)P_h^{\varepsilon-1}}{\left[a + \left(\frac{P_h}{P_b}\right)^{\varepsilon}\right]^2} \tag{23}$$

in which $\varepsilon = 2+3\lambda$ and P_{av} is the average of the pressure head at the current and advanced time steps. This average value has been introduced here in anticipation of the finite difference method that will be used to solve the initial boundary value problem posed in Figure 85.

d. Finite Difference Equations

The Crank-Nicholson method has been used to obtain an approximate numerical solution to the unsaturated flow problem described previously. According to the Crank-Nicholson method, differences of the space derivatives at the advanced time increment are weighted equally with those of the current time increment as the time derivative is approximated with a second order difference centered midway between the time increments. Thus, if central differences are used to approximate the space derivatives, the Crank-Nicholson method approximately evaluates the partial differential equation being solved at a point midway between the time increments and at the given space grid point. This approximation leads to a system of simultaneous algebraic equations, the simultaneous solution of which advances the flow regime through each time increment. This differencing approach is referred to as an implicit method, and provides equations which are stable (i.e., truncation errors do not grow in magnitude for any time increment size).

There are two approaches commonly used in obtaining the difference approximation to the left side (or the space derivative) of Eq. 13. The first approach takes the algebraic derivatives of the product term $K_r(\Delta P_h + k)$ and thereafter differences each remaining derivative. The second approach differences the product term directly. In this second approach a difference of a difference approximation occurs and, therefore, the order of the approximation is not as clearly defined as in the first approach. However, the resulting finite difference equations are simpler. Primarily for this latter reason the second approach is followed here.

Using F_i to designate the ith equation in a system of simultaneous equations, the finite difference approximation to Eq. 13 is:

$$F_i \quad \left[K_{i+\frac{1}{2}} (P_{i+1} - P_i + \Delta z) - K_{i-\frac{1}{2}} (P_i - P_{i-1} + \Delta z)\right]^{k+1}$$

$$- C_1 \frac{|P_{av}|_i^{\lambda-1}}{\left[a + \left(\frac{P_{av}}{P_b}\right)_i^{\lambda}\right]^2} (P_i^{k+1} - P_i^k) + \left[K_{i+\frac{1}{2}} (P_{i+1} - P_i + \Delta z) - \right.$$

$$\left. K_{i-\frac{1}{2}} (P_i - P_{i-1} + \Delta z)\right]^k = 0 \qquad (24)$$

in which the superscript k represents the time increment $k = t/\Delta t$ and i represents the space grid line, i.e., $i = z/\Delta z + 1$,

$$C_1 = \frac{\eta(1-S_r)\ \Delta z^2 \lambda a}{K_o\ \Delta\tau\ P_b^{\lambda}} \qquad (25)$$

$$P_{av} = (P_i^{k+1} + P_i^k)/2 \qquad (26)$$

and the relative hydraulic conductivites are evaluated using average values of capillary pressure as indicated by the subscript. For example

$$K_{i+\frac{1}{2}} = \frac{a}{a + \left(\frac{P_{i+1} + P_i}{2P_b}\right)^{2+3\lambda}} \qquad (27)$$

The subscript i in Eq. 24 takes on the value $i = 2,3, --, n-1$, in which n is the number of the grid point on the ground surface. Special equations for F_1 and F_n are needed for the boundary $z = 0$ and $z = D$ where D is the depth of the unsaturated zone. The equation for F_1 is obtained from the no-flux condition

$$\frac{\partial P_h}{\partial z} = -1 \qquad (28)$$

as long as $P_h < 0$. When P_h equals zero, water will move through the lower boundary of the region. Whenever it is assumed that a water table exists at $z = 0$, then P_h will equal zero at this boundary from the beginning time step $k = 0$. Under such conditions the grid point $i = 1$ has a known value $P_i = 0$ and is a Dirichlet condition and, consequently, no equation for F_1 exists. When this is not the case, however, the finite difference equation for F_1 is obtained by approximating the derivative in Eq. 28 by a second order central difference at $i = 1$ giving $P_o = P_2 + 2\Delta z$, which is substituted for P_o when $i = 1$ in the regular finite difference Eq. 24 to give ($K_{-\frac{1}{2}} = 1$ since it is in the saturated zone),

$$F_1 = \left[K_{1\frac{1}{2}} (P_2 - P_1 + \Delta z) - K_{\frac{1}{2}} (P_1 - P_2 + 3\Delta z)\right]^{k+1} -$$

$$C_1 \frac{\left|P_{av}\right|_i^{\lambda-1}}{\left[a + \left(\frac{P_{av}}{P_b}\right)_i^{\lambda}\right]^2} (P_i^{k+1} - P_i^{k}) + \left[K_{1\frac{1}{2}} (P_2 - P_1 + \Delta z) -\right.$$

$$\left. K_{\frac{1}{2}} (P_1 - P_2 + 3\Delta z)\right]^k = 0 \qquad (29)$$

in which $K_{\frac{1}{2}}$ is evaluated from

$$K_{\frac{1}{2}} = \frac{a}{a + \left(\frac{P_2 + P_1 + 2\Delta z}{2P_b}\right)^{2+3\lambda}}$$

The top boundary will be handled differently depending upon whether the specified flux condition or the specified surface saturation occurs. For the specified surface saturation, no equation F_n is needed since the upper boundary is a Dirichlet condition with P_n computed from the specified saturation or

$$P_n = P_b \left(\frac{a(1-S_r)}{S_n - S_r} - a\right)^{\frac{1}{\lambda}} \qquad (30)$$

in which both a superscript k and k+1 apply to P_n, and S_n is the specified surface saturation. The specified flux condition has been handled by using the regular finite difference equation, i.e.,

$$F_n = \left[K_{n+\frac{1}{2}}\,(P_{n+1} - P_n + \Delta z) - K_{n-\frac{1}{2}}\,(P_n - P_{n-1} + \Delta z)\right]^{k+1}$$

$$-C_1\,P_{ao}{}^{\lambda}\,(P_n{}^{k+1} - P_n{}^{k})/\left[a + \left(\frac{P_{av}}{P_b}\right)^{\lambda}\right]^2 + b_n{}^{k} = 0 \qquad (31)$$

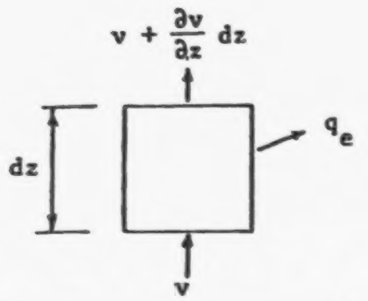
in which $b_n{}^k$ is a repeat of the first terms in the square brackets and the pressure P_{n+1} above the boundary is given by

$$P_{n+1} = P_{n-1} - 2\Delta z\,\left(1 + \frac{q(a + P_n/P_b)^{\varepsilon}}{a\,K_o}\right). \qquad (32)$$

The system of equations, F_i, i = 1, 2 --n-1, n (or F_i, i = 2, 3 --n), must be solved to advance the flow regime through each time step. This system of equations is nonlinear and, consequently, requires some special treatment. The method of solution is described later. It should be noted now, however, that if the surface saturation condition applies on the boundary z = D, then the last equation of the system is dropped or the system consists of F_i, i = 1, 2 --n-1. Also, after the bottom boundary reaches a zero pressure, or if the problem specifies that at t = 0, no equation exists at the first grid point, then the system consists of F_i, i = 2, --n-1 (or n).

e. Evapotranspiration Sink Terms

Transpired water is extracted at depths where plant roots exist in the soil. These depths will depend upon plant species and the period in the plants life cycle. To model this as accurately as possible, the unsaturated model allows for sink terms to exist at the grid point near the surface. To derive the equations which include these sink terms, consider a small one-dimensional element of soil as shown in the sketch on the following page. The water flux transmitted through the



lower boundary is given as v, and that leaving through the upper boundary is given by

$$v + \frac{\partial v}{\partial z}\, dz. \tag{33}$$

Also, the sink removes the flux q_e, which equals the volumetric flowrate Q per unit surface area of evapotranspiration that occurs at this depth. Thus from continuity

$$v - (v + \frac{\partial v}{\partial z}\, dz) - q_e = \frac{\partial \theta}{\partial t}\, dz \tag{34}$$

or

$$\frac{\partial v}{\partial z} = - \frac{\partial \theta}{\partial t} - q_e/dz \quad .$$

Substituting Darcy's Law $v = -K_o\, K_r\, (\frac{\partial P_h}{\partial z} + 1)$ leads to

$$\frac{\partial (K_r\, (\frac{\partial P_h}{\partial z} + 1)}{\partial z} = \frac{\eta}{K_o} \frac{\partial S}{\partial P_h} \frac{\partial P_h}{\partial t} + \frac{q_e}{K_o}\, dz \tag{35}$$

The finite difference approximation of Eq. 35 is

$$F_i = \left[K_{i+\frac{1}{2}}\, (P_{i+1} - P_i + \Delta z) \right]^{k+1} - \frac{C_1 \left| P_{av} \right|^{\lambda-1} (P_i^{k+1} - P_i^{k})}{\left[a + \left(\frac{P_{av}}{P_b} \right)^{2+3\lambda} \right]^2}$$

$$+ b_i^k - \frac{2\Delta t}{K_o} \frac{q_e}{\Delta z} = 0 \quad , \tag{36}$$

which is the same as the regular finite difference Eq. 24 with the addition of the sink term.

f. Solution of Finite Difference Equations.

The general Newton-Raphson iterative method has been utilized in solving the system of nonlinear finite difference equations to advance the solutions through each new time step. The Newton-Raphson method is an iterative method that provides quadratic convergence and, therefore, is well adapted in principle for solving nonlinear finite difference equations from a parabolic partial differential equation; because, from the known values on the current time step, fairly good estimates can be provided with which to start the iteration. In discussing the Newton-Raphson method the system of equations F_i, $i = 1, 2$ --n will be referred to as the equation vector, $\vec{F}$. The unknowns for which the solution is sought are the pressure heads at the advance time with a k+1 superscript. These unknowns P_i^{k+1}, $i = 1, 2$ ---n will be referred to as the unknown vector, $\vec{P}$.

The Newton-Raphson method provides a better approximation to the unknown vector $\vec{P}$ by means of the iterative formula,

$$\vec{P}^{(m+1)} = \vec{P}^{(m)} - (D^{-1})^{(m)} \vec{F}^{(m)} \quad , \tag{37}$$

in which the superscript (m) denotes the iteration number and D^{-1} is the inverse of the Jacobian matrix and for the system of finite difference equations described previously consists of the tridiagonal matrix,

$$D \equiv \begin{bmatrix} \frac{\partial F_1}{\partial P_1} & \frac{\partial F_1}{\partial P_2} & & & & \\ \frac{\partial F_2}{\partial P_1} & \frac{\partial F_2}{\partial P_2} & \frac{\partial F_2}{\partial P_3} & & & \\ & & & \frac{\partial F_{n-1}}{\partial P_{n-2}} & \frac{\partial F_{n-1}}{\partial P_{n-1}} & \frac{\partial F_{n-1}}{\partial P_n} \\ & & & & \frac{\partial F_n}{\partial P_{n-1}} & \frac{\partial F_n}{\partial P_n} \end{bmatrix} , \tag{38}$$

for the case with all equations F_i, $i = 1, 2$ --n. The top row and last row of D are deleted if the saturated surface condition or the $P = 0$ condition exists on the top and bottom boundaries, respectively. Accompanying deletion of the first row, $\partial F_2/\partial P_1$ does not exist. Likely, as F_n is removed $\partial F_{n-1}/\partial P_n$ does not exist.

The actual implementation of Eq. 37 in obtaining a solution in a computer program will take the form,

$$\vec{P}^{(m+1)} = \vec{P}^{(m)} - \vec{X} \quad , \tag{39}$$

in which the vector $\vec{X}$ is the solution to the linear system

$$D^{(m)} \vec{X} = \vec{F}^{(m)} \tag{40}$$

The equations needed for evaluating the individual derivatives in the Jacobian D are given below:

$$\frac{\partial F_1}{\partial P_1} = K_{1\frac{1}{2}} - K_{\frac{1}{2}} + (P_2 - P_1 + \Delta z) \frac{\partial K_{1\frac{1}{2}}}{\partial P_1} - (P_1 - P_2 + 3\Delta z) \frac{\partial K_{\frac{1}{2}}}{\partial P_1}$$

$$+ C_1 \frac{|P_{av}|^{\lambda-1}}{\left[a + \left(\frac{P_{av}}{P_b}\right)^{\lambda}\right]^2} \quad \frac{.5(\lambda-1)(P_i^{k+1} - P_i^{k}) - (P_{av}/P_b)^{\lambda} / \left[a + (P_{av}/P_b)^{\lambda}\right]}{P_{av}} + 1 \tag{41}$$

$$\frac{\partial F_1}{\partial P_2} = K_{1\frac{1}{2}} + K_{\frac{1}{2}} + (P_2 - P_1 + \Delta z)\frac{\partial K_{1\frac{1}{2}}}{\partial P_2} - (P_1 - P_2 - \Delta z)\frac{\partial K_{\frac{1}{2}}}{\partial P_2} \tag{42}$$

in which,

$$\frac{\partial K_{\frac{1}{2}}}{\partial P_2} = \frac{\partial K_{\frac{1}{2}}}{\partial P_1} = \frac{.5 \; a \; \varepsilon \; \left[(P_2 - P_1 - 2\Delta z)/(2P_a)\right]^{\varepsilon} / P_{av}}{\left[a + \left(\frac{P_{av}}{P_b}\right)^{\lambda}\right]^2} \tag{43}$$

$$\frac{\partial F_i}{\partial P_{i-1}} = K_{i-\frac{1}{2}} + (P_i - P_{i-1} + \Delta z) \frac{.5 \; a \; \varepsilon \left(\frac{.5(P_{i-1} + P_i)}{P_b}\right)^{\varepsilon}}{.5(P_{i-1} + P_i) \left[a + \left(\frac{.5(P_{i-1} + P_i)}{P_b}\right)^{\varepsilon}\right]^2} \tag{44}$$

$$\frac{\partial F_i}{\partial P_i} = (P_{i+1} - P_i + \Delta z) \frac{.5 \; a \; \varepsilon \left(\frac{.5(P_{i+1} + P_i)}{P_b}\right)^{\varepsilon}}{.5 \; (P_{i+1} + P_i) \left[a + \left(\frac{.5(P_{i+1} + P_i)}{P_b}\right)^{\varepsilon}\right]^2}$$

$$- (P_i - P_{i-1} + \Delta z) \frac{.5 \; a \; \varepsilon \left(\frac{.5(P_{i-1} + P_i)}{P_b}\right)^{\varepsilon}}{.5 \; (P_{i-1} + P_i) \left[a + \left(\frac{.5(P_{i-1} + P_i)}{P_b}\right)^{2+3\lambda}\right]^2} - K_{i-\frac{1}{2}}$$

$$- K_{i+\frac{1}{2}} + \frac{C_1 \left(\frac{P_{av}}{P_b}\right)^{\lambda}}{P_{av} \left[a + \left(\frac{P_{av}}{P_b}\right)\right]^2} \left(\frac{P^{k+1} - P^k}{P_{av}}\right) \left[.5 \; (\lambda - 1) - \frac{\lambda \left(\frac{P_{av}}{P_b}\right)^{\lambda}}{a + \left(\frac{P_{av}}{P_b}\right)^{\lambda}} + 1.\right] \tag{45}$$

$$\frac{\partial F_i}{\partial P_{i+1}} = K_{i+\frac{1}{2}} - (P_{i+1} - P_i + \Delta z) \frac{.5 \; a \; \varepsilon \left(\frac{.5(P_{i+1} + P_i)}{P_b}\right)^{\varepsilon}}{.5(P_{i+1} + P_i) \left[a + \left(\frac{.5(P_{i+1} + P_i)}{P_b}\right)^{\varepsilon}\right]^2} \tag{46}$$

The solution of the linear system of equations represented by Eq. 40, is accomplished by noting that this is a tridiagonal system with, at most, three non-zero elements on each row: the diagonal element and the elements immediately below and above the diagonal. Either decomposition methods or the Gaussian elimination produce efficient computational methods for solving Eq. 40. One pass to eliminate the elements below the diagonal followed by back substitution produces the solution.

While, in theory, the solution to the above equations by the Newton-Raphson method advances the solution through a time step, the strongly nonlinear equations can, and often do, cause the Newton-Raphson method to fail to produce a solution, particularly if a wetting front exists in the profile in which the water content changes abruptly between consecutive finite difference grid points. For such difficulties, a number of actions may be taken such as reducing the grid space, reducing the time step, and building special additional logic into the computer program to insure that the Newton iteration always produces reasonable estimates for the vector $\vec{P}^{(k+1)}$ at all grid points.

2. Overland Flow Model

After investigating available computer programs capable of handling overland flow on a watershed surface, it was decided to utilize that of Rovey et al, (1977). The FORTRAN program has been acquired, and an effort made to make it fully operational on a stand-alone basis. A number of routine changes were necessary to adapt it to a different computer. At present, there are difficulties in getting adequate performance from this program for some problem solutions that have been attempted. Future efforts will make the necessary modifications to get proper performance and to couple the model to the other component models.

3. Ground-Water Model

a. Approach

Quantification and better understanding of the ground-water systems of the study watersheds can be achieved by digital modeling. Modeling efforts thus far have been for premining flow conditions for watersheds C06 and M09. The model used, described by Trescott (1975) and Trescott and Larson (1976), employs a finite-difference numerical algorithm to arrive at approximate solutions to the partial differential equations that describe ground-water flow. The option used has three layers. Each layer corresponds to an aquifer and consists of an array of approximately 25 x 17 nodes, each node representing an area of 100 feet by 100 feet. The model is quasi-three-dimensional in that vertical flow is simulated only between the layers; within each layer, modeled flow is horizontal. Modifications to the off-the-shelf model allow for (1) flow from the aquifer to springs and streams and from streams to the aquifer, (2) application of recharge to any layer, and (3) water-balance calculation for every layer. Both transient and steady-state simulations are possible, although only steady-state simulation will be discussed in this report.

The model is illustrated schematically in Figure 89. In the top layer, discharge at the outcrop of the underlying confining bed (spring flow and evapotranspiration) is simulated by a line of nodes in the model grid. The discharge rate at these nodes is controlled by a leakage coefficient, confining-bed elevation, and the calculated hydraulic head. In the middle layer discharge at stream nodes (base flow and evapotranspiration) is determined by the head difference between stream surface and aquifer and the leakance of the streambed (vertical hydraulic conductivity divided by bed thickness). Flow from the springs recharging the second layer, QS', is determined by the calculated hydraulic head at the spring node and the leakance assigned to the confining bed at the spring node. This recharge can be controlled by adjusting the leakance. Flow in the deep layer is not simulated; this layer is modeled simply as a receptacle for downward leakage from the middle layer.

Ground-water flow is determined within the model from equations based on Darcy's law, and a conservation principle--flow in must equal flow out of an aquifer-volume element.

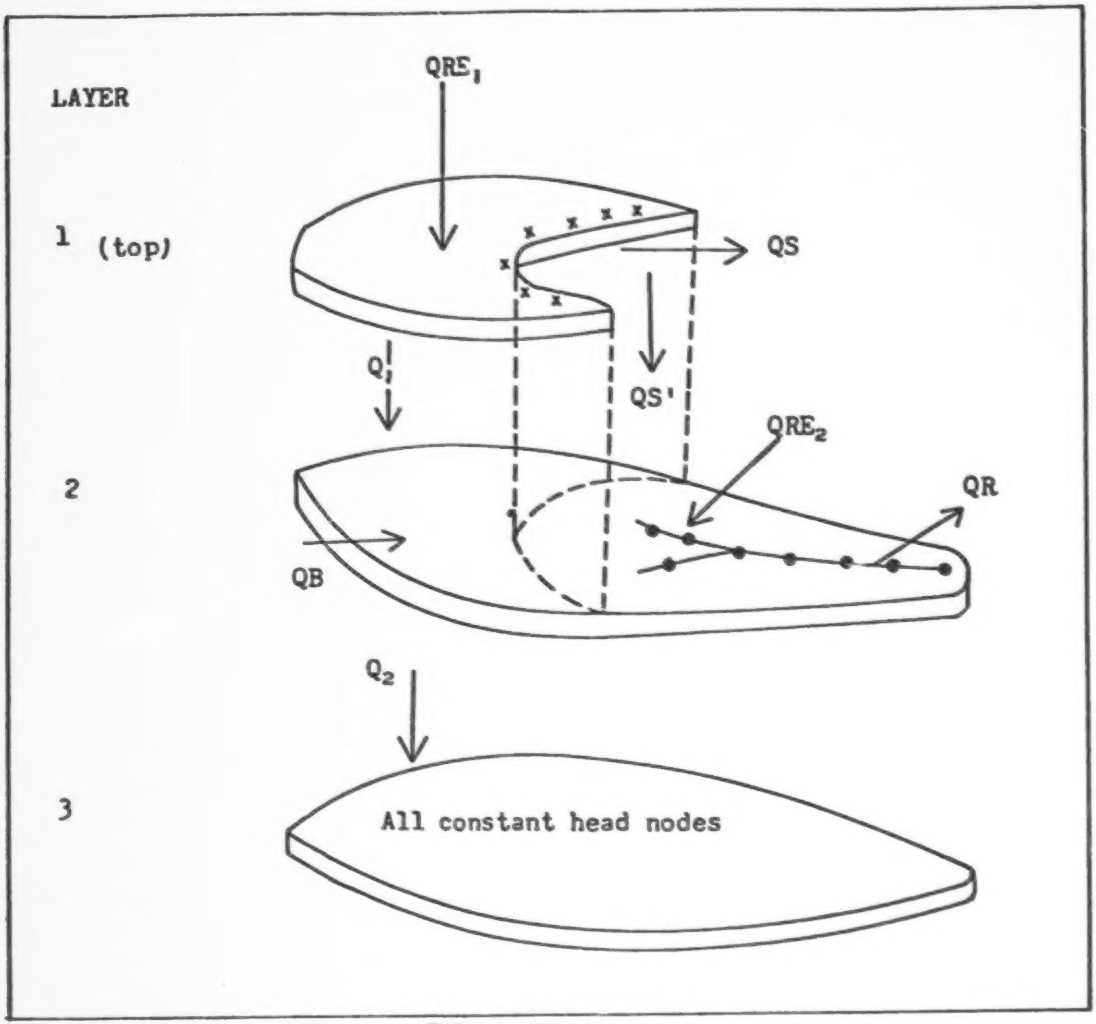
Except for the northwest part of M09, the top aquifer is perched in each watershed and hence is separated from the middle aquifer by an unsaturated zone. This fact along with an assumed, spatially constant recharge rate, allows a simplified but useful discussion of ground-water flow through a volume element of the top aquifer, not incorporating a spring (Figure 90). Let this element be a differential element of height, h, extending from the confining bed to the potentiometric surface (water table). For such an element, conservation requires that:

$$\begin{array}{l} \text{Recharge} \\ \text{to the} \\ \text{element} \end{array} = \begin{array}{l} \text{Net areal flow} \\ \text{out of the} \\ \text{aquifer element} \end{array} + \begin{array}{l} \text{Leakage downward} \\ \text{out of the} \\ \text{element.} \end{array} \qquad (47)$$

This equation is expressed within the model in mathematical form as:

$$QRE = -K\bar{h} \left(\frac{\partial^2 h}{\partial X^2} + \frac{\partial^2 h}{\partial Y^2}\right) + (TK)h \ , \qquad (48)$$

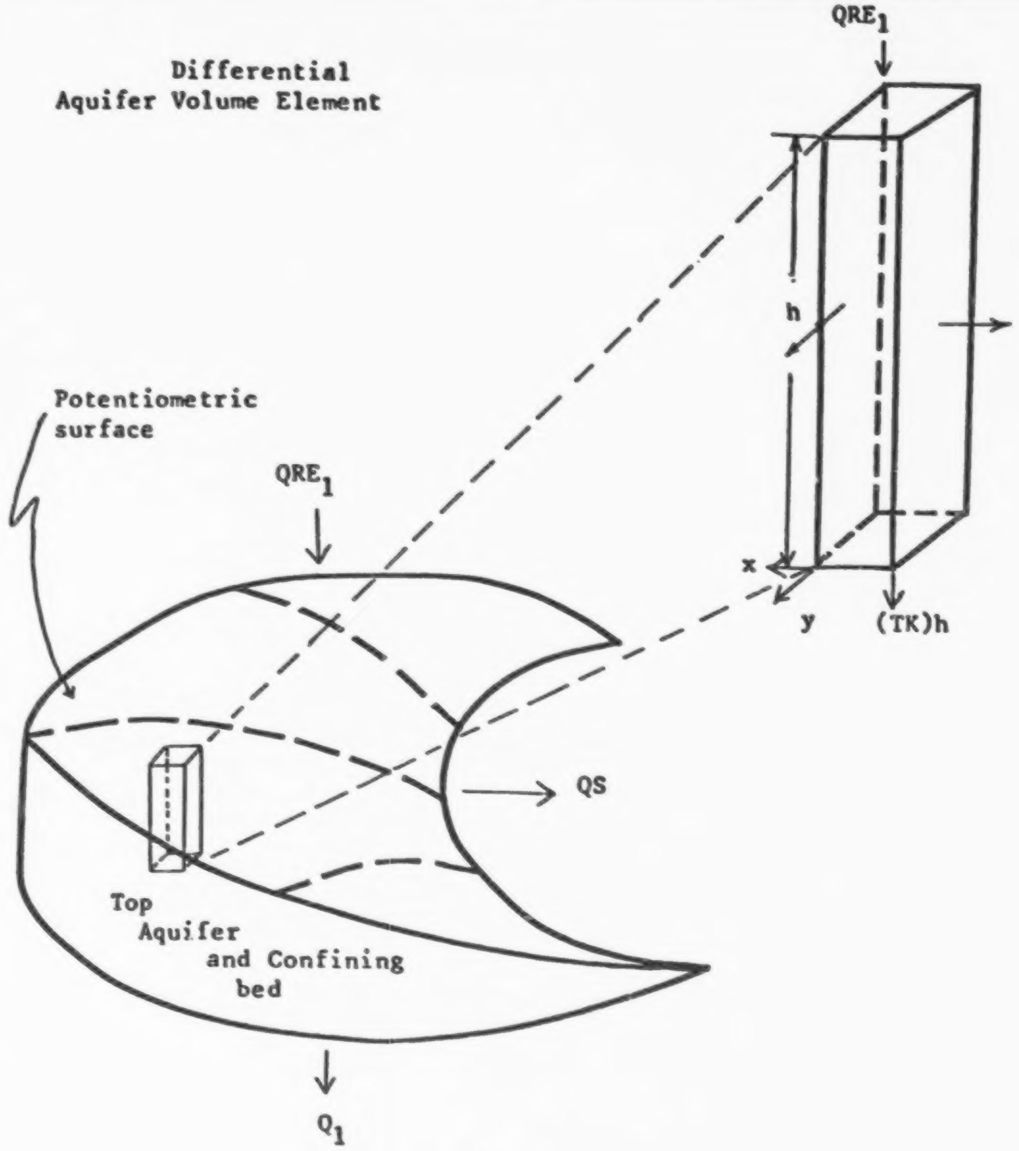
where K is aquifer hydraulic conductivity, $\bar{h}$ is an approximation to the expected head (approximation used to avoid nonlinear equation), h is aquifer head, and TK is confining-bed leakance.


LAYER
QRE_1
1 (top)
QS
Q_1
QS'
QRE_2
2
QR
QB
Q_2
3
All constant head nodes

EXPLANATION

x = spring node
● = stream node
QRE_n = precipitation recharge to layer n
Q_n = leakage from layer n through its bottom confining bed
QS' = recharge to second layer due to spring discharge
QS = surface discharge from top layer (spring flow plus evapotranspiration)
QR = surface discharge from middle layer (net base flow to stream plus evapotranspiration
QB = net underflow across boundary into aquifer

Figure 89. Schematic Diagram of Components of Ground-Water Flow Model


Differential
Aquifer Volume Element
QRE_1
h
x
y
(TK)h
Potentiometric
surface
QRE_1
QS
Top
Aquifer
and Confining
bed
Q_1

QRE_1 = rate of precipitation recharge to top aquifer

Q_1 = leakage from top aquifer through its bottom confining bed

QS = spring flow plus evapotranspiration

(TK)h = confining bed leakance, TK, times head, h, equal to rate of leakage through the confining bed of the differential volume element

Figure 90. Flow Through Volume Element of Top Aquifer

Each term of Eq. 48 represents the corresponding term in the descriptive equation above it. Thereby, areal flow out of the aquifer element decreases as K decreases, and leakage decreases as h decreases.

Several observations can be made now that lead to important modeling guidelines for the top aquifer.

It can be shown by the conservation principle and the boundary conditions of the top aquifer, that recharge per unit area must be greater than or equal to leakage per unit area, or equivalently, that net areal flow into a volume element cannot exist. To show this, a heuristic argument follows.

Assume there exists a net areal flow into an arbitrary volume element; then surrounding elements (of equal areal extent) have a higher average head, and hence more downward leakage (leakance is assumed spatially constant). Because recharge is the same for all elements, these surrounding elements must, therefore, be receiving more areal flow than they are transmitting to the central element (conservation principle). Similarly, the elements surrounding these secondary elements also receive more areal flow than they are transmitting inwardly. Continuing this argument with ever-increasing annular areas, all boundary elements are finally reached. Because boundaries for the top aquifers are either impermeable or outflow boundaries, the elements on these boundaries cannot receive areal flow. Thus, no volume element can receive a net areal influx. Using this fact in combination with Eq. 48 leads to

$$TK \leq QRE/h \, . \qquad (49)$$

Hence, for a given recharge and a given aquifer head, a maximum confining-bed leakance is determined. It follows also that recharge and leakance fix a maximum head that can be generated by a particular simulation. Equation 48 shows that this maximum head is achieved as the hydraulic conductivity approaches zero. Also, simulated top aquifer potentiometric surfaces will not be concave.

It is not the purpose of the simulation of ground-water flow to represent an entire ground-water system in all its complexity. As with any physical description it must be incomplete. This incompleteness has two aspects: one is that observations themselves are inadequate todescribe all the details of the physical system, and the other is that the model is not capable of detailed simulation of all complexities, even if they were known. Incompleteness of knowledge of the ground-water system can be illustrated by the fact that actual ground-water levels are known only at about ten points within each watershed, and the absence of vertical flow within a modeled aquifer is an example of incompleteness inherent in any of the simulations. The prime value of a model lies in its quality as a simplified abstraction. This quality in the present case is most poignantly embodied in the phrase "steady state." Such a state does not exist in nature, but it is a useful idea to consider because its application reveals hydrologic relationships between the various aspects of a problem without concern for the additional complexity of transient phenomena. How this abstraction relates to field observations and its dependency on input and hydrologic judgment is illustrated in Figure 91.

Commonly, steady-state models are used to simulate a time-averaged field state, perhaps incorporating the annual average of all observed components. However, adjacent mining after the beginning of data collection at C06 and M09 caused significant water-level changes in part of the top aquifer. Thus, a useful annual average of associated water-levels was impossible to calculate. Even if such a time-averaged field state could be calculated, such a state in nature would be highly unlikely. Hence, basic error is inherent in almost any attempt to simulate a time-averaged hydrologic state. For these reasons it was thought best to try to simulate instantaneous hydrologic states with steady-state models. For example, simulations of water levels, spring flow, and streamflow as measured in April 1976 for C06 and in May 1976 for M09 were attempted, assuming a recharge rate of 6 inches per year.

Without knowing the exact hydrologic parameters needed for an accurate simulation, the steady-state recharge rate necessary to obtain agreement with observed field conditions cannot be determined. A surplus or small deficit in estimated recharge can be accommodated by altering overall confining-bed leakances, thereby bringing water levels close to field values without greatly affecting the shape of the potentiometric surface. The validity of such an accommodation cannot be checked because vertical leakage is not measured in the field. However, this ignorance implicit in a single steady-state simulation can be explored with transient simulations or steady-state simulations of other instantaneous states.

The ranges of hydrologic parameters used in reported simulations are:

Ground-water recharge = 0.5 ft/year

Aquifer hydraulic conductivity = 10^{-6} to 10^{-8} ft/s

Leakance = $1.5\ (10)^{-9}$ to 10^{-11} s^{-1}

Spring and stream coefficients = 10^{-5} to 10^{-8} s^{-1}

Aquifer hydraulic conductivities used were those suggested by the results of aquifer test analyses (Table 74). Confining-bed leakance ranged from a theoretically determined maximum to a minimum that simulated approximate impermeability. For models constructed according to the above specifications, a 30 percent increase in recharge could result in water table rises of 8 feet. Changes in spring and stream coefficients of two orders of magnitude had only local effects

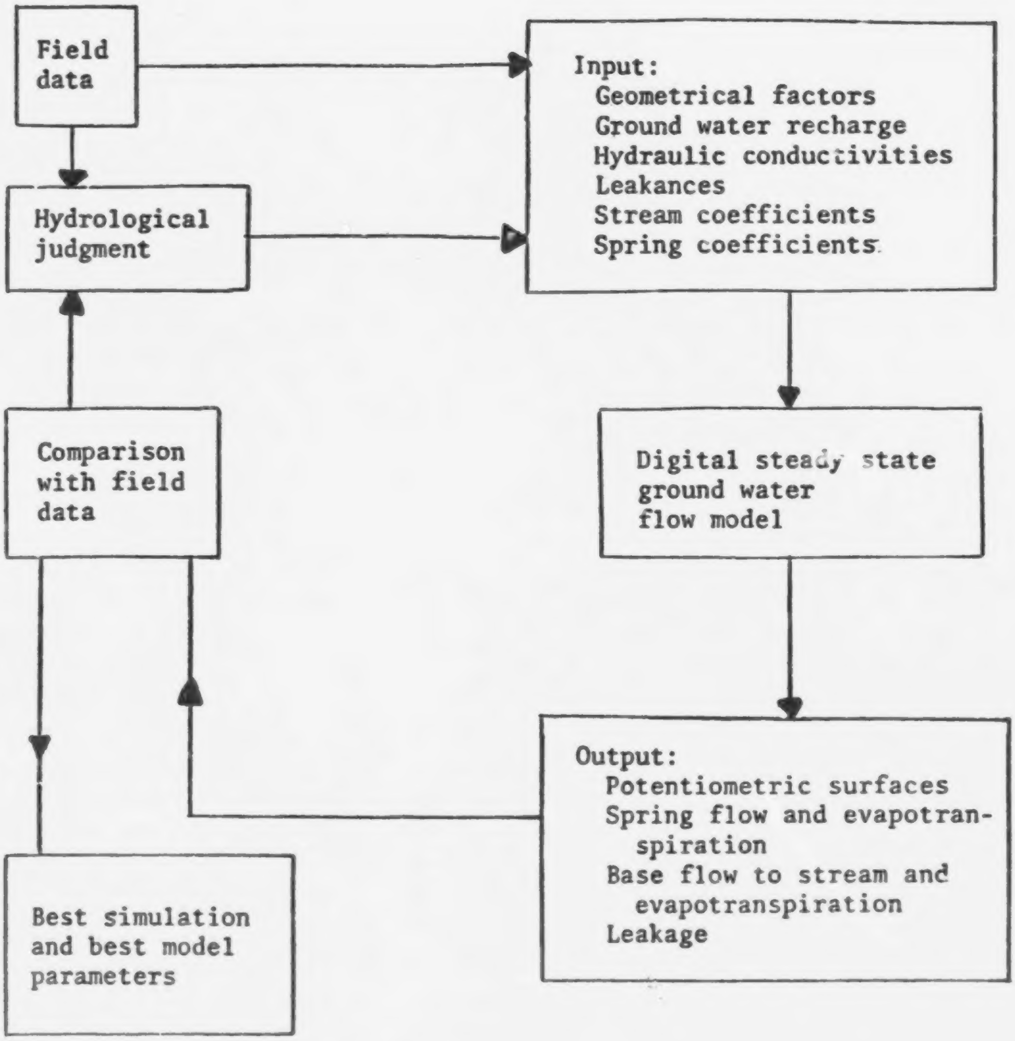

Field data
Hydrological judgment
Input:
Geometrical factors
Ground water recharge
Hydraulic conductivities
Leakances
Stream coefficients
Spring coefficients
Digital steady state ground water flow model
Output:
Potentiometric surfaces
Spring flow and evapotranspiration
Base flow to stream and evapotranspiration
Leakage
Comparison with field data
Best simulation and best model parameters

Figure 91. Flow Chart Illustrating the Use of the Ground-Water Flow Model

on the potentiometric surface and an approximate 15 percent change in simulated spring flow and streamflow. Hence, further consideration of spring and stream coefficients is omitted here. Similarly, constant heads used to simulate boundary flow for the middle aquifer at M09 were observed to have only local effects and to produce small flow rates; hence, they were omitted from most simulations of M09 and replaced by a no-flow boundary.

Simulation efforts for C06 and M09 (discussed below) followed a rule of first investigating the adequacy of simple models (those with identical hydrologic parameters in the top and middle units). Geologic similarity between the units, based on drill-hole data, indicated a possibility that these models would produce realistic simulations.

b. Results and Discussion

(1). Watershed C06. Potentiometric surfaces in the top and middle aquifers were simulated for C06. Profiles of these were compared with April 1976 water levels observed along two sections, W1-1 to W3-1 and W6-1 to W5-1 (well locations are shown in Figure 2). The observed profiles and definitive simulated profiles are in Figure 92.

Simulations A and B (Figure 92) were generated by two of the best simple models. Simulation A gave a much better match to middle-aquifer water levels than Simulation B, whereas little difference in the simulated water levels was noted in the top aquifer. This suggests that a hydraulic conductivity of 3×10^{-6} ft/s may more appropriately have characterized the top and middle aquifers of C06, than one of 5×10^{-7} ft/s.

Simulation C was a successful attempt to improve on simulation B by decreasing the top confining-bed leakance. This change resulted in higher simulated water levels of the middle aquifer, bringing them closer to those observed in the field. Geologic information did not rule out a difference in leakance between the top and middle confining beds. Hence, the model associated with Simulation C could have incorporated a valid hydrologic structure.

The concave shapes of the middle-aquifer potentiometric profiles in Simulations B and C reflected recharge where the aquifer was not overlain by the top confining bed. Though this feature is not evident on the potentiometric map (Figure 66), data were not sufficient to preclude the existence of such head distributions, at least during times of highest rates of recharge.

Computed top-aquifer heads along the east profile (W6-1 to W5-1) were much too high in all simulations. This suggests an areal variation in confining-bed leakance for the top confining bed. Again, this possibility cannot be ruled out geologically, and is thought by the authors to be as likely as a variation within the aquifer itself. A

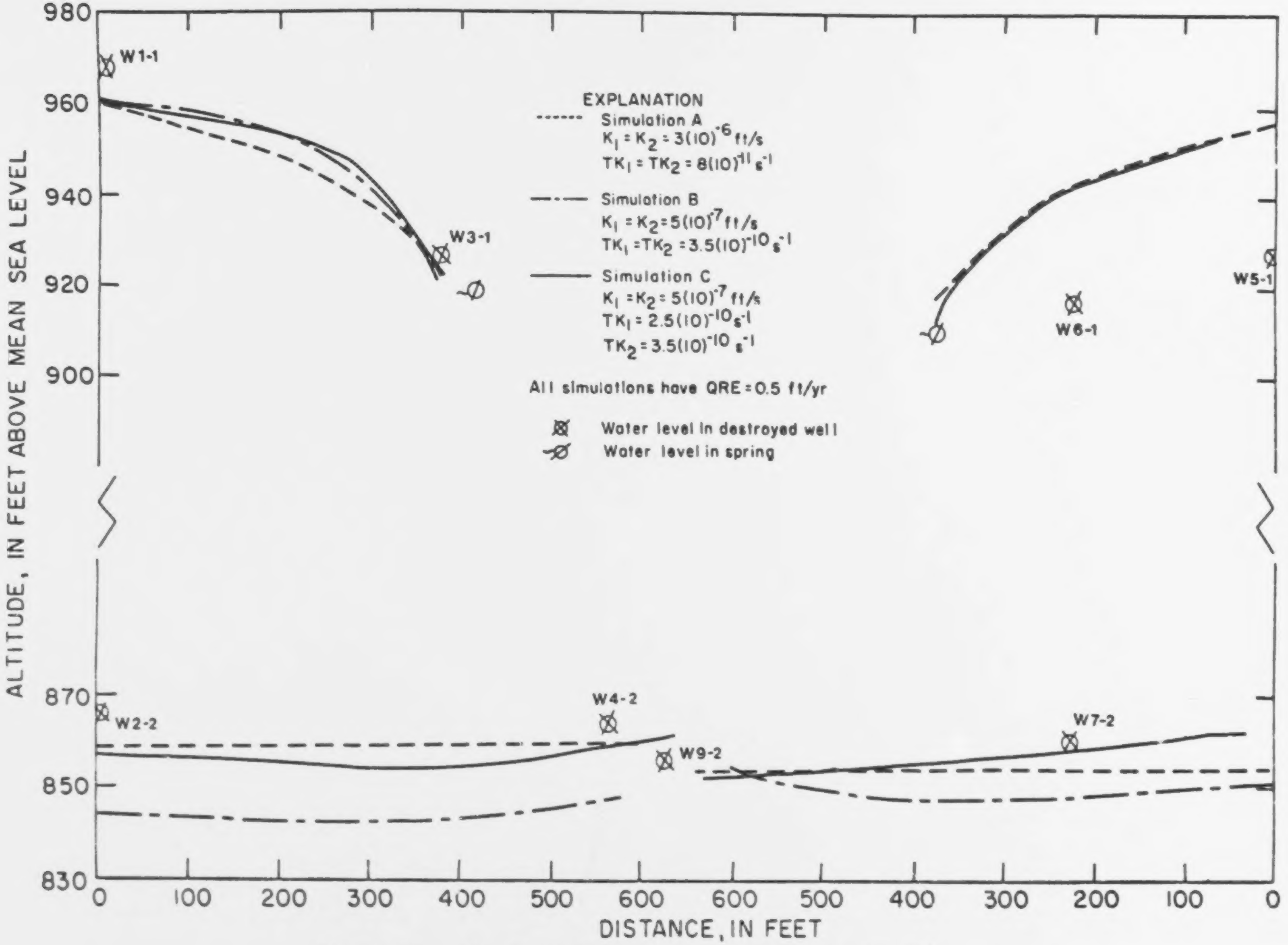


Figure 92. Simulated Potentiometric Profiles for C06

model with a spatially-variable confining-bed leakance has been constructed and a simulation was tried, but the attempt did not converge to a solution. A change to a direct solution method rather than the iteration method now used is contemplated. This change could result in simulations that may be crucial in determining the best steady-state model of ground-water flow in C06.

The water-budget component of spring flow plus evapotranspiration, QS (Table 88), exceeded measured spring flow for April 1976 (Figure 67). Because the field evapotranspiration was unknown, the simulated component of QS was considered to be in agreement with the field value. The water-budget component of base flow plus evapotranspiration, QR, may have been about equal to base flow for April 1976; it is believed that the relatively high measured streamflow during April (Figure 67) was mostly runoff from precipitation and snow melt and that base flow was less than 0.01 ft^3/s as it was during May-August. The two best potentiometric matches, Simulations A and C, show large differences in QS and QR. Field data do not indicate which of these simulations is to be preferred on the basis of its water budget.

(2). Watershed M09. Potentiometric surfaces in the top and middle aquifers were simulated for M09. Profiles of these were compared with May 1976 water levels observed along two sections, W1-1 to W3-1 and W8-1 to W6-1 (well locations are shown in Figure 3). The observed profiles and definitive simulated profiles are shown in Figure 93.

The profiles of Simulation D (Figure 93) represent the closest match to field heads under the restriction that the top and middle units had the same constant hydrologic parameters. However, the water levels generated by this simple approach were not in good agreement with field observations.

Simulation E generated the best match to all the water levels. It was produced by a complicated model simulating different hydraulic conductivities in the top and the middle aquifers and an areal variation in the top confining bed leakance of more than one order of magnitude, increasing from the ground-water divide to the outcrop over the northern half of the watershed. The middle confining bed was assigned a value of leakance between the low and high values for the top confining bed. Drilling-log descriptions of the top confining bed include nothing to indicate a large variation in leakance. Hence, if such a variation did exist, it may have been due to fractures in the underclay away from the ground-water divide. Theoretically, it can be shown that only a variation in top confining-bed leakance as described above (or a large variation in recharge, which seems unlikely) would result in simulated heads that agree with observed W6-1 and W8-1 water levels. Combining this variation with an aquifer hydraulic conductivity of approximately 3×10^{-7} ft/s produces improved simulated head values. In Simulation E, the W7-1 and W8-1 water levels were well matched, as were the W7-2 and W9-2 water levels, even though flow along these two profiles for the most part was in opposite directions.

Table 88. Water Budgets for C06 Simulations.

QRE = precipitation recharge to layer.
Q_n = leakage rate from layer n through its bottom confining bed.
QS = surface discharge from the top layer. (Spring flow plus evapotranspiration.)
QR = surface discharge from middle layer. (Net base flow to stream plus evapotranspiration.)

Simulation A

Top Layer	Middle Layer
QRE = 0.024 ft^3/s	QRE = 0.019 ft^3/s
QS = -.021	Q_1 = .003
Q_1 = -.003	QR = -.014
	Q_2 = -.008

Simulation B

Top Layer	Middle Layer
QRE = 0.024 ft^3/s	QRE = 0.019 ft^3/s
QS = -.009	Q_1 = .014
Q_1 = -.014	QR = -.003
	Q_2 = -.030

Simulation C

Top Layer	Middle Layer
QRE = 0.024 ft^3/s	QRE = 0.019 ft^3/s
QS = -.009	Q_1 = .014
Q_1 = -.014	QR = -.005
	Q_2 = -.028

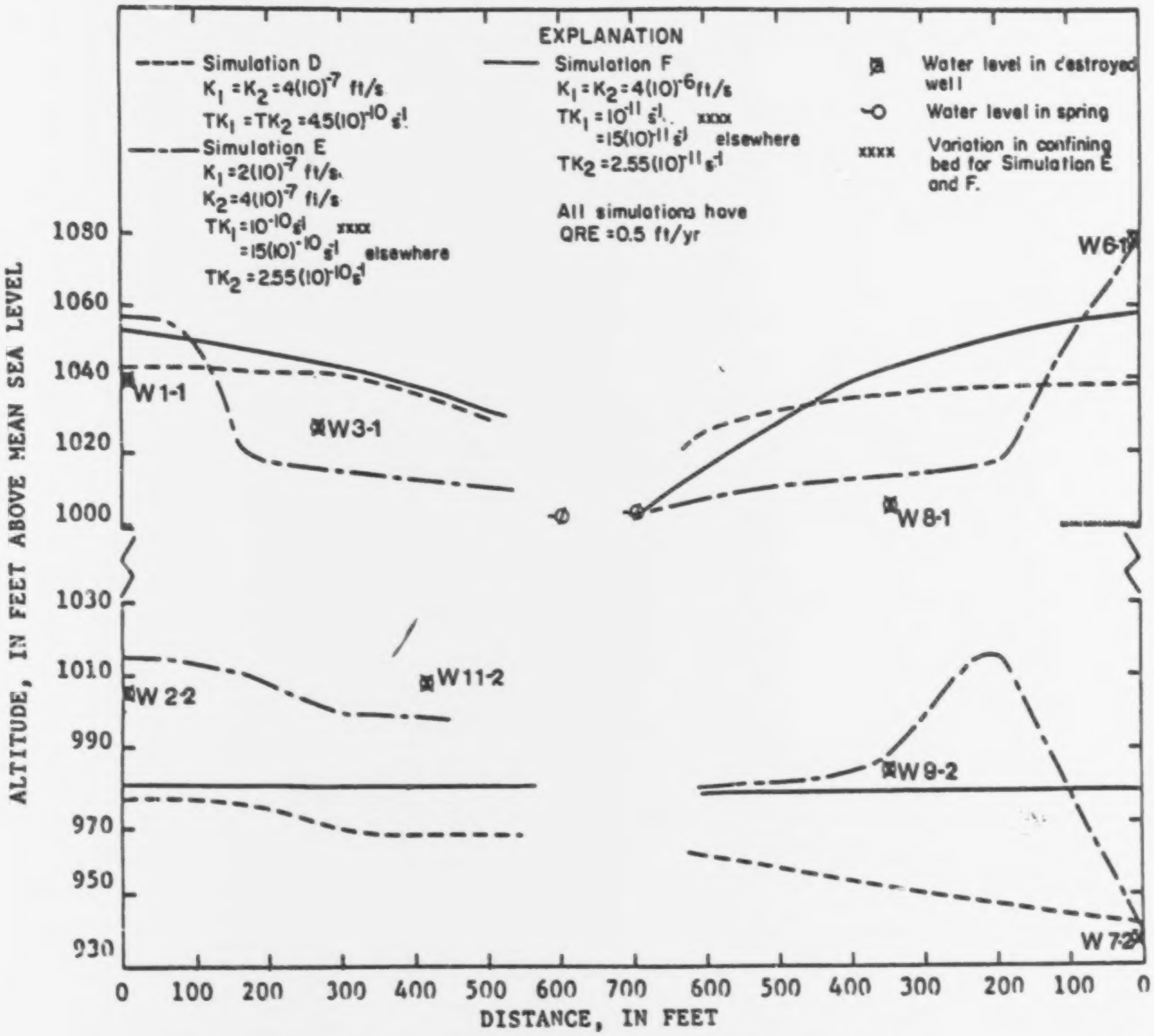


Figure 93. Simulated Potentiometric Profiles for M09

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The water-level profiles generated by Simulation F show the best that can be expected if the hydraulic conductivity in Simulation E is increased by approximately an order of magnitude. These profiles do not have the sharply varying slopes necessary for a good match of observed water levels. In particular, the W6-1 to W8-1 profile could never be matched with such a large hydraulic conductivity, allowing any conceivable confining-bed leakance variation. Hence, such large conductivities must be ruled out for no more complicated models of M09 than are considered here.

Simulations involving lower hydraulic conductivity values (on the order of 10^{-8} ft/s) along with other parameters used in Simulation E, failed to converge to a solution. Solutions are expected from the direct solution method mentioned previously. From theoretical considerations, it seems likely that such models will be capable of exhibiting the necessary sharp slope changes with a smaller range of areal leakance variation in the top confining bed. If this occurs, then the new model will be an improvement on the ones discussed here because it will generate good matches to field data with a more justifiable areal leakance variation.

Water-budget data for M09 simulations are presented in Table 89. Spring flow plus evapotranspiration (QS) for the best M09 potentiometric simulation (Simulation E) was greater than observed spring flow (Figure 71). Because the field evapotranspiration was unknown, the simulated spring flow plus evapotranspiration was considered to be in agreement with field values. Although streamflow data are not available for May 1976, simulated base flow plus evapotranspiration (QR) agreed approximately with base flow during June-December (less than 0.01 ft^3/s), (Figure 71). Again, as in the C06 discussion, comparison with field water-budget data does not yield any preferred simulations.

Table 89. Water Budgets for M09 Simulations.

QRE = precipitation recharge to layer.
Q_n = leakage rate from layer n through its bottom confining bed.
QS = surface discharge from the top layer. (Spring flow plus evapotranspiration.)
QR = surface discharge from middle layer. (Net base flow to stream plus evapotranspiration.)

Top Layer	Middle Layer
Simulation D	
QRE = 0.032 ft^3/s	QRE = 0.012 ft^3/s
QS = -.004	Q_1 = .028
Q_1 = -.028	QB = .002*
	QR = -.000
	Q_2 = -.042
Simulation E	
QRE = 0.032 ft^3/s	QRE = 0.012 ft^3/s
QS = -.004	Q_1 = .028
Q_1 = -.028	QR = -.002
	Q_2 = -.038
Simulation F	
QRE = 0.032 ft^3/s	QRE = 0.012 ft^3/s
QS = -.026	Q_1 = .006
Q_1 = -.006	QR = -.015
	Q_2 = -.003

* Boundary flow was eliminated in simulations E and F.

IX. ECONOMICS

A. General

During the past decade a number of Federal and Ohio laws have been enacted to encourage reclamation of areas disturbed by surface mining. These laws have been implemented by Federal and state agencies which have issued regulations, monitored reclamation activities, and enforced provision of the regulations.

The mining industry has sought to comply with these regulations. At the same time, the industry has complained of the legal and administrative burden of these reclamation requirements. Complex regulations have to be studied, reports must be filed, performance bonds must be acquired, license must be purchased, permits must be obtained, and so forth. These costs are real. They consume resources that could be employed elsewhere. Yet few studies have identified their magnitude. The overall objective of this study is to estimate these costs.

Economic analysis of strip mine reclamation is proceeding in three stages. First, legal and administrative costs of complying with Federal and Ohio regulations have been estimated. Second, the costs of the reclamation process are to be estimated. Third, benefits of reclamation to the surrounding community are to be projected.

The first stage, estimating legal and administrative costs, has been completed and publications from this stage are being planned. Work is now in progress on assessing the costs and benefits of reclamation. However, these stages are in their infancy with data collection being the primary activity. This report concentrates on describing research in the first stage and summarizing results of this stage.

B. Legal and Administrative Costs

1. Study Objectives

Specific objectives of the first stage were to:

1. Review state and Federal legislation which affect legal and administrative costs,
2. Compare the impact of the existing state law with the impact of the new Federal law,
3. Estimate legal and administrative costs incurred by companies in complying with state and Federal regulations, and

4. Estimate costs incurred by state and Federal agencies in establishing, monitoring, and enforcing reclamation regulations.

2. Results and Discussion

Objectives 1 and 2 were met by reviewing and summarizing current Ohio strip mine laws and the new Federal law. A prepared manuscript titled, "Legal and Administrative Costs of Strip Mine Reclamation in Ohio," summarizes state and Federal provisions and is presented in a publications supplement to the Phase I Report. In general, the Ohio Strip Mine Reclamation Law has required operators to meet a number of stringent regulations since 1972. Compared to other states, these regulations were relatively severe and placed Ohio's strip mine operators at a competitive disadvantage. The 1977 Federal Surface Mining and Control Act initiated a Federal program of regulating reclamation. Many similarities were found between Ohio and Federal law. In many cases though, the Federal law is more restrictive. But the legal and administrative costs borne by coal companies under the Ohio law appear to be good surrogates for these costs under the new Federal law.

To accomplish Objective 3, a survey of Ohio coal producers was conducted. A questionnaire was developed with the assistance of the coal mining industry and Division of Reclamation personnel. The questionnaire was mailed to all Ohio coal mine producers, followed up with post cards two weeks later, and random telephone calls.

Cost estimates provided by each mine operator were converted into an estimate of the present value of legal and administrative costs per acre for each permit. Regression analysis was used to identify the relationship between (a) cost per permit acre, and (b) number of acres in the permit. Also, the relationship was identified between (a) cost per coal ton, and (b) coal tons per acre and number of acres in the permit.

Regression results indicated that size of the permit is an important variable in estimating legal and administrative costs (Table 90). A strip mine operator with a 10-acre permit would incur legal and administrative costs of nearly $300 per affected acre. An operator with a permit of 25 acres might expect to incur legal and administrative costs of about $180 per affected acre. Larger operators with permits having 200 acres affected could expect legal and administrative costs of about $110 per acre. The relationship between costs per acre and acres in permit is depicted graphically in Figure 94.

Results in Table 91 show the relationship between legal and administrative costs per ton and the acres in the permit and the coal tonnage per acre. These costs are illustrated in Figure 95. The mean

Table 90. Legal and Administrative Costs Per Acre as a Function of Affected Acres in the Permit.

Affected Acres	Legal and Administrative Costs/Acre*
5	$492.31
10	$296.23
15	$230.87
20	$198.19
25	$178.58
35	$156.17
50	$139.17
75	$126.29
100	$119.76
200	$109.95
400	$105.05

*Present value of all legal and administrative costs over the expected life of the permit. Discount rate of 8 percent is used.

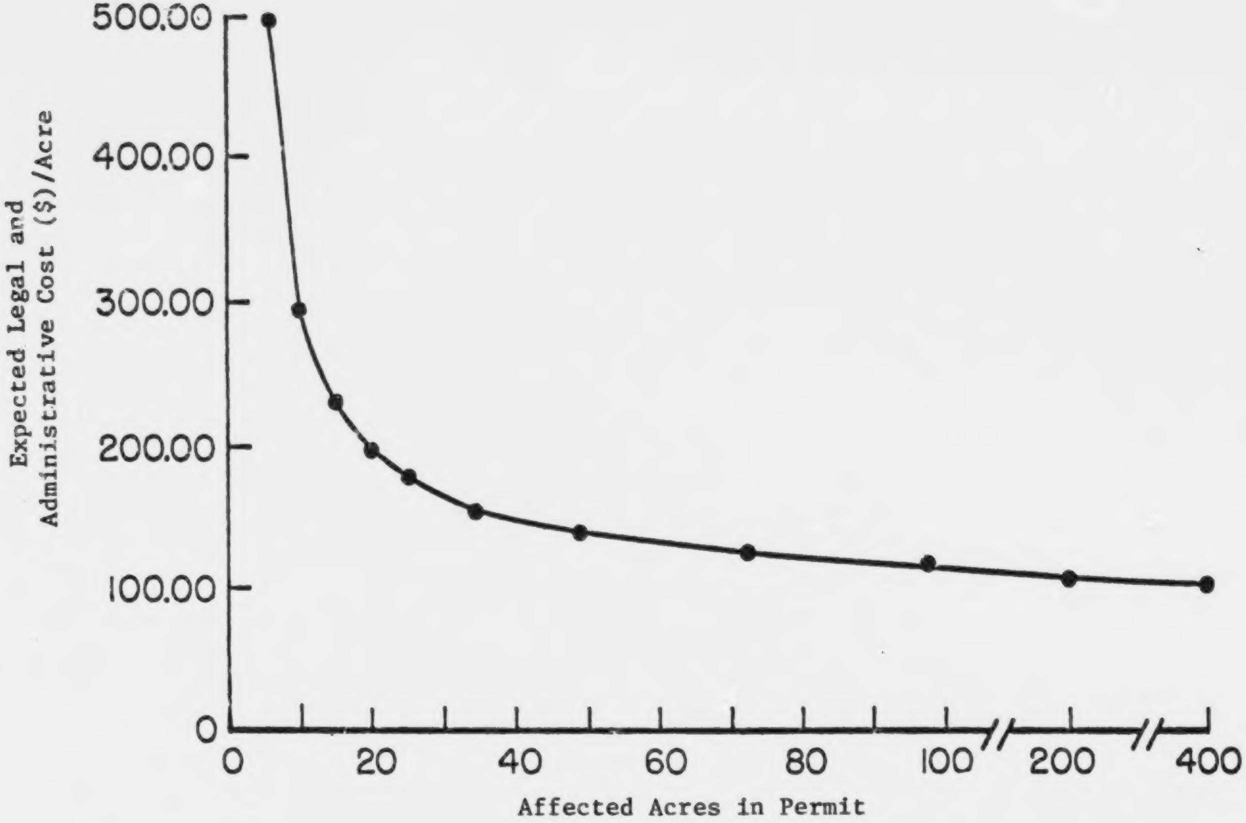

Figure 94. The Average Expected Premining Cost Per Acre Given the Affected Acreage in the Permit

Table 91. Legal and Administrative Costs Per Ton as a Function of Acres in the Permit and Coal Yield (Tons Per Affected Acre).

Affected Acres (1)	Tons Per Affected Acre 1120 (2)	2423 (3)	3726 (4)
		$ per ton	
5	0.354	0.287	0.221
10	0.240	0.174	0.108
15	0.203	0.136	0.070
20	0.184	0.117	0.051
25	0.172	0.105	0.039
35	0.159	0.092	0.026
50	0.150	0.083	0.017
75	0.142	0.076	0.009
100	0.138	0.072	0.005
200	0.133	0.066	0.00009
400	0.130	0.063	-----

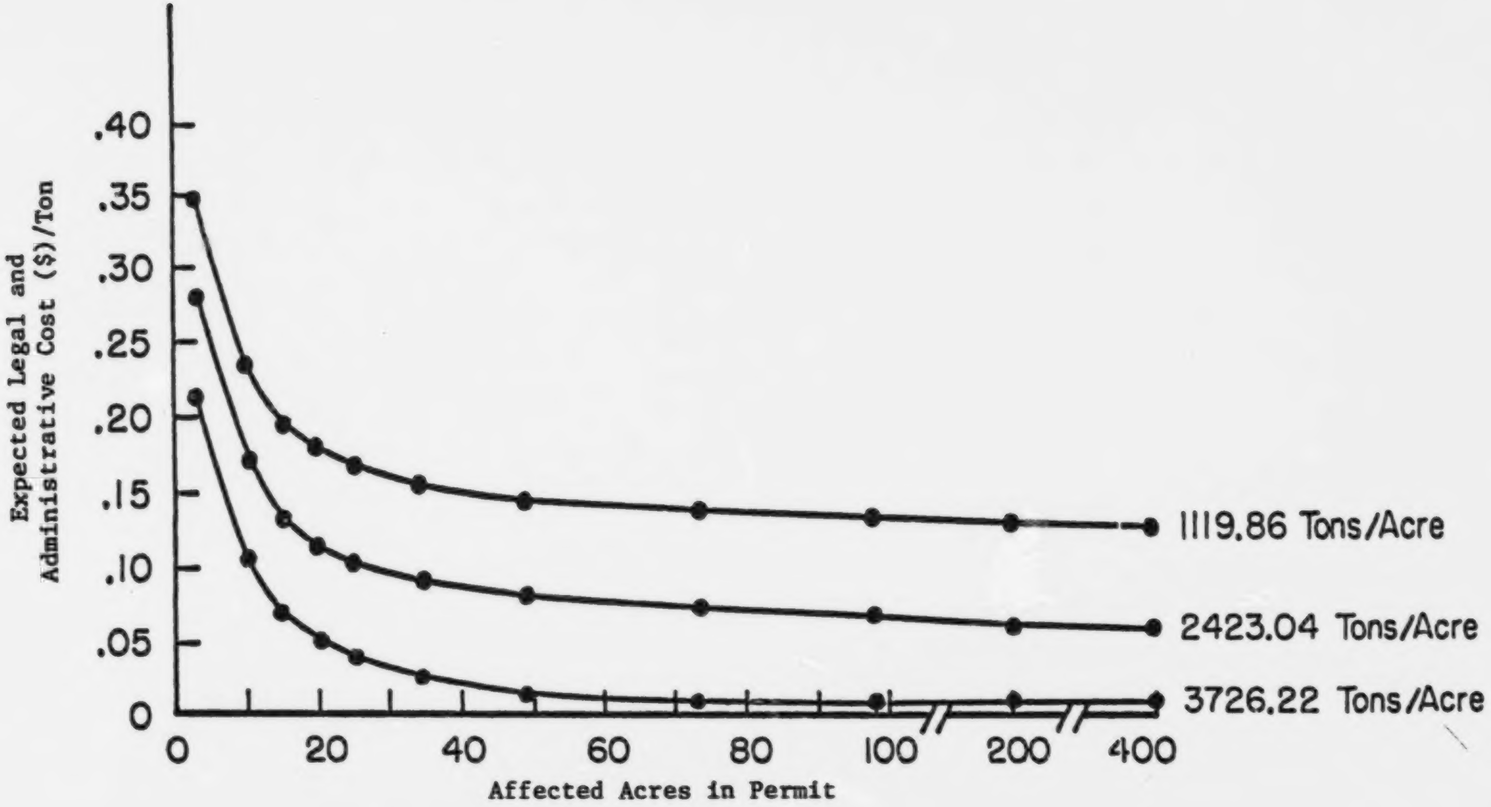

Figure 95. The Average Expected Premining Cost Per Ton Given the Affected Acreage in the Permit Under Alternative Levels of Coal Production Per Affected Acre

permit in the survey had 2423 coal tons per permit acre. With this yield, a 20-acre permit could expect legal and administrative costs to total about 11.7¢ per coal ton.

Again, economies of size were apparent as higher yields and more acreage in the permit resulted in lower costs per ton. For the large permit with a large proportion of the affected acreage being mined, legal and administrative costs per ton were minute.

There was wide variability in the coal yield from each permit. A standard deviation of 1303.18 tons per acre was computed from survey results. Some permits had a large proportion of the affected acreage being mined for coal, while others had little coal acreage and/or a narrow seam thickness. Column 2 in Table 91 shows the costs per ton for those low yielding permits which had yields of one standard deviation less than the mean. A 20-acre permit had legal and administrative costs of 18.4¢ per ton. Column 4 in Table 91 shows costs per ton for those permits with yields one standard deviation above the mean. Legal and administrative costs totaled only 5.1¢ per ton for this 20-acre permit.

Objective 4, estimating state and Federal costs in establishing, monitoring, and enforcing regulations, was accomplished by investigating the costs of Ohio's Division of Reclamation. This agency has been responsible for administering a relatively severe strip mine law, and costs are thought to be representative of costs in administering the Federal program. For the 1977 fiscal year, approximately $720,000 was spent on the monitoring and enforcing of the Ohio Strip Mine Law. However, receipts from license and permit fees paid by the industry totaled $989,000 for the same period.

The Ohio Environmental Protection Agency administers the National Pollution Discharge Elimination System (NPDES) to control water pollution from strip mines in Ohio. Net costs of monitoring and enforcing the NPDES permits were about $60,000 in 1977.

The estimates of legal and administrative costs for the industry included the license and permit fees paid by the industry. Thus, the state's administrative costs and the industry's administrative costs were not additive. Rather, the industry cost estimates included the costs incurred by the regulatory bodies.

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APPENDIX A

Table A-1 Description and Characterization Data for Dekalb Loam (Watershed C06).

Table A-2 Description and Characterization Data for Westmoreland Silt Loam (Watershed C06).

Table A-3 Description and Characterization Data for Coshocton Silt Loam (Watershed C06).

Table A-4 Description and Characterization Data for Otwell Silt Loam (Watershed C06).

Table A-5 Description and Characterization Data for Coshocton Silt Loam (Watershed C06).

Table A-6 Description and Characterization Data for Lowell Silt Loam (Watershed M09).

Table A-7 Description and Characterization Data for Upshur Silt Loam (Watershed M09).

Table A-8 Description and Characterization Data for Westmore Silt Loam (Watershed M09).

Table A-9 Description and Characterization Data for Licking Silt Loam (Watershed M09).

Table A-10 Description and Characterization Data for Brookside Silty Clay Loam (Watershed M09).

Table A-1. Description and Characterization Data for Dekalb Loam (Watershed C06)

```
SOIL TYPE: DEKALB LOAM                       COUNTY: COSHOCTON  SITE: CS-28
PEDON CLASSIFICATION: LOAMY SKELETAL MIXED MESIC TYPIC DYSTROCHREPTS
LOCATION: 1200 FT E AND 600 FT S OF NW CORNER  SEC. 22 T.4N R.5W
PHYSIOGRAPHY: SIDESLOPE, BACKSLOPE                 ELEVATION: 950
TOPOGRAPHY: VERY STEEP               % SLOPE: 40    ASPECT: S-SW
DRAINAGE: WELL                                     VEGETATION: FOREST
COLLECTORS: SMECK/HALL/RIDDLE                      DATE: 7/20/76
PARENT MATERIALS: SANDSTONE AND SHALE


HORIZON   DEPTH
            IN
A1         0 -3
        10YR3/2-LOAM; MODERATE FINE GRANULAR
     STRUCTURE; VERY FRIABLE; MANY MEDIUM ROOTS;
     20% COARSE FRAGMENTS; ABRUPT SMOOTH BOUNDARY.
A21        3 -11
        10YR5/4-SANDY LOAM; WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; VERY FRIABLE; COMMON FINE ROOTS;
     45% COARSE FRAGMENTS; CLEAR SMOOTH BOUNDARY.
A22        11-21
        10YR5/4-SANDY LOAM; WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; VERY FRIABLE; FEW FINE ROOTS;
     45% COARSE FRAGMENTS; GRADUAL WAVY BOUNDARY.
B1         21-37
        10YR5/6-SANDY LOAM; WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; FEW FINE ROOTS;
     THIN VERY PATCHY 7.5YR5/6 COATINGS ON ROCK FRAGMENTS;
     80% COARSE FRAGMENTS; GRADUAL WAVY BOUNDARY.
B21T       37-48
        10YR5/6-SANDY LOAM; WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; FEW FINE ROOTS;
     MEDIUM VERY PATCHY 7.5YR5/6 COATINGS ON ROCK FRAGMENTS;
     THICK CONTINUOUS 10YR5/6 BRIDGING ON PEDS AND IN PORES;
     80% COARSE FRAGMENTS; GRADUAL WAVY BOUNDARY.
B22T       48-59
        10YR5/6-SANDY LOAM; WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; FEW FINE ROOTS;
     MEDIUM VERY PATCHY 7.5YR5/6 COATINGS ON ROCK FRAGMENTS;
     THICK CONTINUOUS 10YR5/6 BRIDGING ON PEDS AND IN PORES;
     80% COARSE FRAGMENTS; GRADUAL WAVY BOUNDARY.
IIB23T     59-68
        10YR5/4-SANDY LOAM; WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; FEW FINE ROOTS;
     THICK PATCHY 7.5YR4/4 COATINGS ON ROCK FRAGMENTS;
     THICK CONTINUOUS 10YR5/6 BRIDGING ON PEDS AND IN PORES;
     50% COARSE FRAGMENTS; GRADUAL WAVY BOUNDARY.
IIB24T     68-76
        10YR5/3-SANDY LOAM; WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; FEW FINE ROOTS;
     THICK VERY PATCHY 7.5YR4/4 COATINGS ON ROCK FRAGMENTS;
     THICK CONTINUOUS 10YR5/6 BRIDGING ON PEDS AND IN PORES;
     50% COARSE FRAGMENTS; ABRUPT WAVY BOUNDARY.
IIIB3      76-84
        10YR5/4-SILTY CLAY LOAM; FEW MEDIUM FAINT 10YR5/6 AND
     FEW MEDIUM FAINT 10YR5/2 MOTTLES; WEAK FINE SUBANGULAR BLOCKY
     STRUCTURE; FIRM; FEW ROOTS;
     35% COARSE FRAGMENTS;


NOTE: SANDSTONE IN COLLUVIUM ABOVE 59 IN IS SOFT. THAT BELOW IS HARDER
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Table A-1 (Cont't). Description and Characterization Data for Dekalb Loam (Watershed C06)

SOIL SERIES: DEKALB
SITE: CS-28

COUNTY: COSHOCTON
DATE: 7/20/76

DEPTH IN	HORIZON	CO FRAG %>2mm	PARTICLE SIZE DISTRIBUTION (%<2mm)										TEXT CLASS
			SAND					SILT			CLAY		
			VC,C	M	FI	VFI	TOT	FI	VF	TOT	FI	TOT	
0- 3	A1	37.8	6.6	12.3	33.2	7.2	59.3	18.2	5.0	32.0	1.4	8.7	SL
3-11	A21	38.6	11.9	13.5	31.4	7.3	64.1	18.4	4.8	29.5	1.1	6.4	FSL
11-21	A22	33.1	14.5	15.2	30.2	7.0	66.9	16.7	4.6	26.4	1.5	6.7	FSL
21-37	B1	26.9	16.4	18.8	29.8	5.9	70.9	14.9	5.1	21.8	0.3	7.3	SL
37-48	B21T	35.3	21.9	20.3	31.5	4.7	78.4	10.0	3.8	14.3	0.6	7.3	LS
48-59	B22T	13.2	19.9	24.0	30.9	5.2	80.0	9.5	3.4	12.1	2.0	7.9	LS
59-68	IIB23T	9.2	16.0	24.6	31.5	4.8	76.9	9.8	3.9	14.8	2.1	8.3	FSL
68-76	IIB24T	11.2	18.4	24.8	31.3	5.4	79.9	9.9	4.2	12.5	1.9	7.6	LS
76-84	IIIB3	20.1	14.5	3.3	5.6	8.2	31.6	35.1	9.8	53.6	2.2	14.8	SIL

DEPTH IN	pH		ORG C	EQ,%			EXCH CATIONS MEQ/100g					BASE SAT,%
	WAT	CaCl		CALC	DOLO	CARB	H	Ca	Mg	K	SUM	
0- 3	4.7	4.1	2.16				8.5	1.5	0.5	0.31	10.8	21
3-11	4.5	4.0	0.45				4.4	0.3	0.1	0.15	5.0	11
11-21	4.5	4.1	0.20				3.6	0.2	0.1	0.13	4.0	10
21-37	4.8	4.1	0.18				3.6	0.4	0.2	0.16	4.4	17
37-48	5.2	4.4	0.14				2.4	0.7	0.8	0.15	4.1	40
48-59	5.2	4.5	0.10				2.5	0.9	1.1	0.14	4.6	46
59-68	5.2	4.5	0.12				2.1	1.2	1.2	0.16	4.7	54
68-76	5.1	4.4	0.09				2.3	1.2	1.3	0.15	5.0	53
76-84	4.6	4.1	0.27				8.1	2.6	3.5	0.25	14.5	43

Table A-2. Description and Characterization Data for Westmoreland Silt Loam (Watershed C06)

```
SOIL TYPE: WESTMORELAND SILT LOAM        COUNTY: COSHOCTON  SITE: CS-29
PEDON CLASSIFICATION: FINE-LOAMY MIXED MESIC TYPIC HAPLUDALF
LOCATION: 900FT E AND 1100FT S OF NW CORNER SEC. 22 T.4N R.5W
PHYSIOGRAPHY: SUMMIT                             ELEVATION: 1020 FT.
TOPOGRAPHY: GENTLY SLOPING          % SLOPE: 4      ASPECT: S
DRAINAGE: WELL                                   VEGETATION: FOREST
COLLECTORS: SMECK/HALL/RIDDLE                    DATE: 7/30/76
PARENT MATERIALS: WISCONSINAN LOESS, SILTSTONE


HORIZON   DEPTH
            IN
A11         0 -1
        10YR4/2-SILT LOAM; STRONG FINE GRANULAR
    STRUCTURE; VERY FRIABLE; MANY ROOTS;
    ABRUPT WAVY BOUNDARY.
A12         1 -7
        10YR4/3-SILT LOAM; WEAK MEDIUM SUBANGULAR BLOCKY
    PARTING TO MODERATE MEDIUM GRANULAR STRUCTURE; FRIABLE; MANY ROOTS;
    CLEAR SMOOTH BOUNDARY.
B1          7 -12
        10YR4/6-SILT LOAM; MODERATE FINE SUBANGULAR BLOCKY
    STRUCTURE; FRIABLE; COMMON ROOTS;
    CLEAR SMOOTH BOUNDARY.
B21T        12-16
        10YR4/6-HEAVY SILT LOAM; MODERATE MEDIUM SUBANGULAR BLOCKY
    STRUCTURE; FRIABLE; FEW ROOTS;
    THIN VERY PATCHY 10YR4/6 ARGILLANS ON FACES;
    5% COARSE FRAGMENTS; CLEAR SMOOTH BOUNDARY.
IIB22T      16-21
        10YR4/4-SILTY CLAY LOAM; MODERATE MEDIUM SUBANGULAR BLOCKY
    STRUCTURE; FRIABLE; FEW ROOTS;
    THIN PATCHY 10YR4/6 ARGILLANS ON FACES;
    MEDIUM CONTINUOUS 10YR4/6 ARGILLANS ON ROCK FRAGMENTS;
    12% COARSE FRAGMENTS; CLEAR WAVY BOUNDARY.
IIB3T       21-33
        10YR5/4-SILTY CLAY LOAM; WEAK MEDIUM SUBANGULAR BLOCKY STRUCTURE; FIRM;
    THICK PATCHY 10YR4/6 ARGILLANS ON ROCK FRAGMENTS;
    55% COARSE FRAGMENTS; ABRUPT WAVY BOUNDARY.


NOTE: BEDROCK IS SILT WITH SOME INTERBEDDED SANDSTONE.
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Table A-2 (Cont'd). Description and Characterization Data for Westmoreland Silt Loam (Watershed C06)

SOIL SERIES: WESTMORELAND　　COUNTY: COSHOCTON
SITE: CS-29　　DATE: 7/30/76

DEPTH	HORIZON	CO	PARTICLE SIZE DISTRIBUTION (%<2mm)										TEXT
IN		FRAG	SAND					SILT			CLAY		CLASS
		%>2mm	VC,C	M	FI	VFI	TOT	FI	VF	TOT	FI	TOT	
0- 1	A11	3.7	1.7	0.5	0.6	0.7	3.5	50.2	12.2	76.9	4.4	19.6	SIL
1- 7	A12	2.3	2.3	0.9	1.1	0.5	4.8	56.6	14.4	80.5	3.3	14.7	SIL
7-12	B1	2.8	1.5	0.5	0.7	1.8	4.5	52.3	12.5	73.1	5.9	22.4	SIL
12-16	B21T	7.3	2.6	0.4	0.5	1.7	5.2	48.9	12.3	67.0	8.7	27.6	SICL
16-21	IIB22T	31.2	6.3	0.7	0.7	1.3	9.0	45.2	14.9	55.4	9.8	35.6	SICL
21-27	IIB3T	43.7	10.0	1.0	1.0	0.9	12.9	41.8	16.9	47.0	9.3	40.1	SIC
27-33	IIB3T	47.6	16.2	1.8	1.8	1.0	20.8	43.3	16.8	46.1	7.4	33.1	CL

DEPTH	pH		ORG	EQ,%			EXCH CATIONS MEQ/100g					BASE
IN	WAT	CaCl	C	CALC	DOLO	CARB	H	Ca	Mg	K	SUM	SAT,%
0- 1	6.1	5.5	4.90				11.9	14.9	2.3	0.71	29.8	60
1- 7	4.9	4.2	1.32				9.7	2.0	0.5	0.38	12.6	22
7-12	5.1	4.3	0.52				7.6	3.1	0.7	0.20	11.6	34
12-16	4.8	4.1	0.39				8.7	4.1	0.8	0.27	13.9	37
16-21	4.8	4.2	0.33				10.3	5.1	1.6	0.31	17.3	40
21-27	4.9	4.2	0.25				9.2	9.0	3.3	0.48	22.0	58
27-33	4.9	4.5	0.33				7.3	8.9	3.2	0.48	19.9	63

Table A-3. Description and Characterization Data for Coshocton Silt Loam (Watershed C06)

```
SOIL TYPE: COSHOCTON SILT LOAM          COUNTY: COSHOCTON  SITE: CS-30
PEDON CLASSIFICATION: FINE LOAMY MIXED MESIC AQULTIC HAPLUDALF
LOCATION: 1700 FT E AND 700 FT S OF NW CORNER SEC. 22 T.4N R.5W
PHYSIOGRAPHY: NOSESLOPE, BACKSLOPE               ELEVATION: 920
TOPOGRAPHY: MODERATELY STEEP        % SLOPE: 30    ASPECT: S
DRAINAGE: MODERATELY WELL                        VEGETATION: FOREST
COLLECTORS: SMECK/HALL/RIDDLE                    DATE: 7/30/76
PARENT MATERIALS: COLLUVIUM, SHALE


HORIZON   DEPTH
            IN
A1          0 -3
        10YR3/2-SILT LOAM; STRONG FINE GRANULAR
     STRUCTURE; VERY FRIABLE; MANY ROOTS;
     ABRUPT SMOOTH BOUNDARY.
A2          3 -8
        10YR6/3-SILT LOAM; MODERATE MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; COMMON ROOTS;
     10% COARSE FRAGMENTS; CLEAR WAVY BOUNDARY.
B11         8 -14
        10YR6/4-SILTY CLAY LOAM; COMMON MEDIUM DISTINCT 7.5YR5/6 AND
     FEW MEDIUM FAINT 10YR6/1 MOTTLES; MODERATE MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; FEW ROOTS;
     6% COARSE FRAGMENTS; CLEAR WAVY BOUNDARY.
B12         14-18
        10YR6/4-SILTY CLAY LOAM; COMMON MEDIUM DISTINCT 7.5YR5/6 AND
     COMMON MEDIUM FAINT 10YR6/1 MOTTLES; MODERATE MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; FEW ROOTS;
     FEW 10YR2/1 FERRO-MANGANS ON FACES;
     CLEAR WAVY BOUNDARY.
B21T        18-25
        10YR6/1-SILTY CLAY LOAM; COMMON MEDIUM DISTINCT 7.5YR5/6 MOTTLES;
     MODERATE MEDIUM SUBANGULAR BLOCKY STRUCTURE; FIRM; FEW ROOTS;
     THIN PATCHY 2.5Y6/2 ARGILLANS ON FACES;
     6% COARSE FRAGMENTS; CLEAR WAVY BOUNDARY.
B22T        25-31
        10YR6/1-HEAVY SILTY CLAY LOAM; COMMON MEDIUM DISTINCT 7.5YR5/6 MOTTLES;
     MODERATE MEDIUM SUBANGULAR BLOCKY PARTING TO WEAK MEDIUM
     PLATY STRUCTURE; FIRM; FEW ROOTS;
     THIN PATCHY 10YR6/1 ARGILLANS ON FACES;
     12% COARSE FRAGMENTS; CLEAR WAVY BOUNDARY.
B3T         31-45
        10YR6/3-HEAVY SILTY CLAY LOAM; MANY COARSE FAINT 10YR6/1 AND
     MANY COARSE DISTINCT 7.5YR5/6 MOTTLES; WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FIRM; FEW ROOTS;
     THIN VERY PATCHY 2.5Y6/2 ARGILLANS ON FACES;
     45% COARSE FRAGMENTS; CLEAR SMOOTH BOUNDARY.
```

Table A-3 (Cont'd). Description and Characterization Data for Coshocton Silt Loam (Watershed C06)

SOIL SERIES: COSHOCTON
SITE: CS-30

COUNTY: COSHOCTON
DATE: 7/30/76

DEPTH	HORIZON	CO	PARTICLE SIZE DISTRIBUTION (%<2mm)										TEXT
IN		FRAG	SAND					SILT			CLAY		CLASS
		%>2mm	VC,C	M	FI	VFI	TOT	FI	VF	TOT	FI	TOT	
0- 3	A1	8.0	8.6	7.9	12.8	4.9	34.2	33.2	11.1	48.6	3.3	17.2	L
3- 8	A2	19.4	12.4	8.1	12.0	5.1	37.6	32.9	10.2	45.0	1.8	17.4	L
8-14	B11	12.2	9.4	4.5	7.3	4.8	26.0	36.7	11.8	48.9	5.1	25.1	L
14-18	B12	7.3	6.9	3.6	5.6	5.6	21.7	35.6	11.5	48.9	7.1	29.4	CL
18-25	B21T	1.6	3.3	1.5	2.8	5.0	12.6	36.2	12.7	51.1	10.8	36.3	SICL
25-31	B22T	7.6	4.3	0.6	1.2	5.7	11.8	39.0	13.7	52.4	9.7	35.8	SICL
31-38	B3T	14.1	10.4	0.9	0.9	2.8	15.0	39.6	14.6	53.3	7.6	31.7	SICL
38-45	B3T	9.5	5.6	0.6	1.3	6.6	14.1	42.1	14.7	54.8	6.6	31.1	SICL
45-52	CR	16.2	5.6	0.9	4.2	9.8	20.5	36.6	13.3	50.4	5.6	29.1	CL
52-58	CR	10.1	1.7	0.3	0.7	2.3	5.0	53.2	16.9	65.5	5.4	29.5	SICL
58-65	CR	8.0	2.6	0.3	0.7	4.7	8.3	49.3	15.9	64.3	4.8	27.4	SICL
65-71	CR	7.2	2.9	0.6	1.5	8.8	13.8	43.5	14.3	59.9	4.6	26.3	SIL

DEPTH	pH		ORG	EQ,%			EXCH CATIONS MEQ/100g					BASE
IN	WAT	CaCl	C	CALC	DOLO	CARB	H	Ca	Mg	K	SUM	SAT,%
0- 3	5.3	4.7	2.96				8.8	6.9	0.7	0.47	16.9	47
3- 8	5.2	4.6	0.81				5.3	2.9	0.6	0.25	9.0	41
8-14	4.7	4.1	0.49				7.7	2.2	0.5	0.18	10.6	27
14-18	4.5	3.8	0.44				8.4	2.0	0.6	0.17	11.2	24
18-25	4.4	3.6	0.37				9.6	1.9	1.2	0.36	13.1	26
25-31	4.3	3.7	0.24				9.7	1.6	1.8	0.22	13.3	27
31-38	4.3	3.7	0.20				9.6	1.5	2.3	0.22	13.6	29
38-45	4.3	3.8	0.16				7.9	1.5	2.5	0.22	12.1	34
45-52	4.3	4.0	0.22				7.0	1.8	3.1	0.20	12.1	42
52-58	4.7	4.2	0.21				5.3	3.1	4.4	0.27	13.1	59
58-65	5.0	4.6	0.20				4.1	3.7	4.7	0.27	12.8	67
65-71	5.5	5.1	0.26				4.1	4.3	4.5	0.25	13.2	68

Table A-4. Description and Characterization Data for Otwell Silt Loam (Watershed C06)

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SOIL TYPE: OTWELL SILT LOAM               COUNTY: COSHOCTON  SITE: CS-31
PEDON CLASSIFICATION: FINE-LOAMY MIXED MESIC AQUIC FRAGIUDALF
LOCATION: 2200 FT E AND 1200 FT S OF NW CORNER SEC. 22 T.4N R.5W
PHYSIOGRAPHY: BLACKWATER TERRACE                 ELEVATION: 840
TOPOGRAPHY: STRONGLY SLOPING          % SLOPE: 21    ASPECT: WEST
DRAINAGE: MODERATELY WELL                        VEGETATION: FOREST
COLLECTORS: SMECK/HALL/RIDDLE                    DATE: 8/19/76
PARENT MATERIALS: COLLUVIUM, WISCONSINAN LACUSTRINE

HORIZON   DEPTH
            IN
AP1        0 -2
        10YR3/2-SILT LOAM; MODERATE FINE GRANULAR
     STRUCTURE; VERY FRIABLE; MANY ROOTS;
     8% COARSE FRAGMENTS; CLEAR SMOOTH BOUNDARY.
AP2        2 -6
        10YR4/3-SILT LOAM; MANY COARSE DISTINCT 10YR3/2 MOTTLES;
     MODERATE MEDIUM SUBANGULAR BLOCKY PARTING TO MODERATE MEDIUM
     GRANULAR STRUCTURE; FRIABLE; COMMON ROOTS;
     8% COARSE FRAGMENTS; CLEAR SMOOTH BOUNDARY.
B1         6 -12
        10YR4/6-SILT LOAM; MODERATE MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; FEW ROOTS;
     3% COARSE FRAGMENTS; GRADUAL SMOOTH BOUNDARY.
B21T       12-17
        10YR4/6-HEAVY SILT LOAM; MODERATE MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; FEW ROOTS;
     THIN CONTINUOUS 10YR5/4 COATINGS ON FACES;
     CLEAR SMOOTH BOUNDARY.
B22T       17-24
        10YR5/4-HEAVY SILT LOAM; FEW FINE FAINT 10YR5/6 AND
     FEW FINE FAINT 10YR5/2 MOTTLES; WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FRIABLE; FEW ROOTS;
     THIN CONTINUOUS 10YR5/3 COATINGS ON FACES;
     ABRUPT WAVY BOUNDARY.
BX1        24-36
        10YR4/4-HEAVY LOAM; STRONG COARSE PRISMATIC
     PARTING TO WEAK MEDIUM SUBANGULAR BLOCKY STRUCTURE; VERY FIRM;
     THICK CONTINUOUS 10YR5/3 SILANS ON VERTICAL FACES;
     THICK CONTINUOUS 10YR5/1 ARGILLANS ON FACES;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX;
     CLEAR SMOOTH BOUNDARY.
BX2        36-42
        10YR4/4-CLAY LOAM; STRONG VERY COARSE PRISMATIC
     PARTING TO WEAK MEDIUM SUBANGULAR BLOCKY STRUCTURE; VERY FIRM;
     THICK CONTINUOUS 10YR5/1 ARGILLANS ON FACES;
     THICK CONTINUOUS 10YR5/6 IRON RICH ZONES SUBCUTANEOUSLY;
     MANY 10YR2/1 CONCRETIONS IN THE MATRIX;
     CLEAR SMOOTH BOUNDARY.
BX3        42-53
        10YR4/4-CLAY LOAM; STRONG VERY COARSE PRISMATIC
     PARTING TO WEAK MEDIUM SUBANGULAR BLOCKY STRUCTURE; VERY FIRM;
     THICK CONTINUOUS 10YR5/1 ARGILLANS ON FACES;
     THICK CONTINUOUS 10YR5/6 IRON RICH ZONES SUBCUTANEOUSLY;
     COMMON N2/0 CONCRETIONS IN THE MATRIX;
     GRADUAL SMOOTH BOUNDARY.
B31T       53-60
        10YR5/4-SILT LOAM; STRONG VERY COARSE PRISMATIC STRUCTURE; FIRM;
     THICK CONTINUOUS 10YR5/1 ARGILLANS ON FACES;
     THICK CONTINUOUS 10YR5/6 IRON RICH ZONES SUBCUTANEOUSLY;
     GRADUAL SMOOTH BOUNDARY.
B32T       60-67
        10YR5/4-SILT LOAM; STRONG VERY COARSE PRISMATIC STRUCTURE; FIRM;
     THICK CONTINUOUS 5Y5/1 ARGILLANS ON FACES;
     THICK CONTINUOUS 10YR5/6 IRON RICH ZONES SUBCUTANEOUSLY;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX;
     GRADUAL SMOOTH BOUNDARY.
C1         67-75
        10YR5/4-HEAVY SILT LOAM; MASSIVE; FIRM;
     THICK CONTINUOUS 5Y5/1 ARGILLANS ON VERTICAL FACES;
     THICK CONTINUOUS 10YR5/6 IRON RICH ZONES SUBCUTANEOUSLY;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX

C2         75-86
        10YR5/4-HEAVY SILT LOAM; MASSIVE; FIRM;
     THICK CONTINUOUS 5Y5/1 ARGILLANS ON VERTICAL FACES;
     THICK CONTINUOUS 10YR5/6 IRON RICH ZONES SUBCUTANEOUSLY;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX

C3         86-144
        10YR6/2-SILT LOAM; MANY COARSE PROMINANT 7.5YR5/8 MOTTLES;
     MASSIVE; FRIABLE;
     FEW 10YR2/1 FERRO-MANGANS IN THE MATRIX
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Table A-4 (Cont'd). Description and Characterization Data for Otwell Silt Loam (Watershed C06)

SOIL SERIES: OTWELL
SITE: CS-31

COUNTY: COSHOCTON
DATE: 8/19/76

DEPTH IN	HORIZON	CO FRAG	PARTICLE SIZE DISTRIBUTION (%<2mm)										TEXT CLASS
			SAND					SILT			CLAY		
		%>2mm	VC,C	M	FI	VFI	TOT	FI	VF	TOT	FI	TOT	
0- 2	AP1	7.7	5.2	3.1	6.0	3.7	18.0	41.8	14.1	59.2	5.1	22.8	SIL
2- 6	AP2	6.7	5.7	3.5	7.0	4.7	20.9	46.4	15.6	59.9	2.3	19.2	SIL
6-12	B1	2.6	6.2	3.9	6.8	4.3	21.2	42.9	13.2	55.3	3.9	23.5	SIL
12-17	B21T	0.9	6.4	4.3	6.5	3.9	21.1	39.1	10.3	53.0	6.0	25.9	SIL
17-24	B22T	1.4	4.6	3.2	5.5	3.7	17.0	38.4	10.8	57.6	8.4	25.4	SIL
24-30	BX1	1.0	3.6	3.8	8.5	6.4	22.3	32.2	9.2	52.6	10.7	25.1	SIL
30-36	BX1	0.7	3.0	3.8	8.8	6.6	22.2	29.9	7.7	51.0	13.1	26.8	SIL
36-42	BX2	1.2	4.2	5.0	9.2	5.9	24.3	29.8	6.8	48.9	11.9	26.8	L
42-48	BX3	0.5	2.0	2.2	4.4	4.5	13.1	37.6	9.8	57.7	12.9	29.2	SICL
48-53	BX3	0.4	2.3	1.8	3.6	4.4	12.1	37.7	10.0	58.3	12.6	29.6	SICL
53-60	B31T	0.2	1.0	0.7	1.7	3.5	6.9	41.0	9.0	66.3	12.4	26.8	SIL
60-67	B32T	0.0	1.1	1.3	3.0	4.8	10.2	37.2	7.2	65.1	10.7	24.7	SIL
67-75	C1	0.2	1.4	1.9	3.2	3.7	10.2	40.6	8.4	65.1	10.4	24.7	SIL
75-86	C2	0.2	1.2	1.2	2.4	4.3	9.1	39.7	8.4	66.6	11.4	24.3	SIL

DEPTH IN	pH		ORG	EQ,%			EXCH CATIONS MEQ/100g					BASE
	WAT	CaCl	C	CALC	DOLO	CARB	H	Ca	Mg	K	SUM	SAT,%
0- 2	5.7	5.3	4.57				12.6	9.0	2.3	0.53	24.4	48
2- 6	4.9	4.2	1.31				10.4	1.0	0.5	0.25	12.1	14
6-12	4.9	4.4	0.67				9.4	1.2	0.7	0.22	11.5	18
12-17	4.7	4.2	0.36				9.7	1.1	0.8	0.22	11.8	17
17-24	4.8	4.1	0.29				10.9	1.2	1.2	0.25	13.6	19
24-30	4.8	4.1	0.25				10.8	1.5	0.5	0.25	13.1	17
30-36	5.0	4.2	0.27				10.3	2.4	0.8	0.30	13.8	25
36-42	4.8	4.2	0.30				9.1	3.2	1.0	0.35	13.7	33
42-48	5.2	4.5	0.37				8.0	4.7	1.3	0.38	14.4	44
48-53	5.4	4.9	0.49				6.3	6.7	7.5	0.39	20.9	69
53-60	6.6	5.9	0.46				3.3	8.5	8.2	0.37	20.4	83
60-67	6.9	6.3	0.39				2.0	7.5	7.5	0.36	17.4	88
67-75	6.5	6.1	0.30				1.6	7.6	7.6	0.35	17.1	90
75-86	6.9	6.4	0.28				1.5	7.7	7.6	0.36	17.2	91

Table A-5. Description and Characterization Data for Coshocton Silt Loam (Watershed C06)

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SOIL TYPE: COSHOCTON SILT LOAM            COUNTY: COSHOCTON  SITE: CS-32
PEDON CLASSIFICATION: FINE LOAMY MIXED MESIC AQUIC HAPLUDALF.
LOCATION: 1400FT E AND 1200FT S OF NW CORNER SEC. 22 T.4N R.5W
PHYSIOGRAPHY: BENCH                                ELEVATION: 900'
TOPOGRAPHY: MODERATELY SLOPING      % SLOPE: 7      ASPECT: EAST
DRAINAGE: SOMEWHAT POORLY                          VEGETATION: FOREST
COLLECTORS: SMECK/HALL/RIDDLE                      DATE: 8/26/76
PARENT MATERIALS: COLLUVIUM


HORIZON   DEPTH
           IN
AP1        0 -6
        10YR3/2-SILT LOAM; MODERATE MEDIUM GRANULAR
     STRUCTURE; FRIABLE; MANY FINE ROOTS;
     5% COARSE FRAGMENTS; CLEAR SMOOTH BOUNDARY.
AP2        6 -9
        10YR5/2-SILT LOAM; COMMON FINE DISTINCT 7.5YR5/6 MOTTLES;
     WEAK MEDIUM SUBANGULAR BLOCKY STRUCTURE; FRIABLE; MANY FINE ROOTS;
     FEW 7.5YR5/8 CONCRETIONS IN THE MATRIX;
     5% COARSE FRAGMENTS; CLEAR WAVY BOUNDARY.
B11        9 -14
        10YR6/3-SILT LOAM; FEW FINE FAINT 10YR5/6 MOTTLES;
     WEAK FINE SUBANGULAR BLOCKY STRUCTURE; FRIABLE; FEW FINE ROOTS;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX;
     16% COARSE FRAGMENTS. GRADUAL SMOOTH BOUNDARY.
B12T       14-21
        10YR6/2-CLAY LOAM; MANY MEDIUM DISTINCT 10YR5/6 AND
     COMMON FINE PROMINANT 7.5YR5/8 MOTTLES; MODERATE FINE SUBANGULAR BLOCKY
     STRUCTURE; FIRM; FEW FINE ROOTS;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX;
     THIN PATCHY 10YR6/2 ARGILLANS ON FACES;
     16% COARSE FRAGMENTS; GRADUAL WAVY BOUNDARY.
B21T       21-30
        10YR5/6-CLAY LOAM; MANY MEDIUM DISTINCT 7.5YR4/4 AND
     MANY MEDIUM FAINT 7.5YR5/6 MOTTLES; MODERATE MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FIRM; FEW FINE ROOTS;
     MANY 10YR2/1 CONCRETIONS IN THE MATRIX;
     THICK CONTINUOUS 10YR6/1 ARGILLANS ON FACES;
     25% COARSE FRAGMENTS; GRADUAL WAVY BOUNDARY.
B22T       30-36
        10YR5/6-CLAY LOAM; COMMON MEDIUM FAINT 7.5YR5/6 MOTTLES;
     WEAK MEDIUM PLATY PARTING TO MODERATE MEDIUM
     SUBANGULAR BLOCKY STRUCTURE; FIRM; FEW ROOTS;
     THICK PATCHY 10YR6/1 ARGILLANS ON HORIZONTAL FACES;
     THICK PATCHY 7.5YR5/1 ARGILLANS ON HORIZONTAL FACES;
     20% COARSE FRAGMENTS; GRADUAL WAVY BOUNDARY.
B31T       36-42
        10YR5/6-SILT LOAM; COMMON MEDIUM DISTINCT 7.5YR5/4 MOTTLES;
     WEAK COARSE SUBANGULAR BLOCKY STRUCTURE; FIRM;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX;
     THICK CONTINUOUS 10YR5/1 ARGILLANS ON FACES;
     15% COARSE FRAGMENTS; GRADUAL WAVY BOUNDARY.
B32T       42-48
        10YR5/4-SILT LOAM; COMMON MEDIUM DISTINCT 7.5YR5/6 MOTTLES;
     WEAK COARSE PLATY STRUCTURE; FIRM;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX;
     THIN PATCHY 10YR5/1 ARGILLANS ON FACES;
     THIN PATCHY 10YR6/1 ARGILLANS ON VERTICAL FACES;
     GRADUAL WAVY BOUNDARY.
C1         48-58
        10YR5/4-SILT LOAM; COMMON MEDIUM DISTINCT 7.5YR5/6 MOTTLES;
     WEAK COARSE PLATY STRUCTURE; FIRM;
     FEW 10YR2/1 CONCRETIONS IN THE MATRIX;
     THIN VERY PATCHY 10YR6/1 ARGILLANS ON VERTICAL FACES;
     GRADUAL WAVY BOUNDARY.
C2         58-64
        10YR5/4-SILT LOAM; MASSIVE

C3         64-72
        10YR5/4-SILT LOAM; MASSIVE; FIRM;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX;
     THIN VERY PATCHY 10YR6/1 ARGILLANS ON VERTICAL FACES;
     MEDIUM CONTINUOUS 7.5YR5/6 IRON RICH ZONES SUBCUTANEOUSLY;
     10% COARSE FRAGMENTS
C4         72-78
        10YR5/4-SILT LOAM; MASSIVE; FIRM;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX;
     THIN VERY PATCHY 10YR6/1 ARGILLANS ON VERTICAL FACES;
     MEDIUM CONTINUOUS 7.5YR5/6 IRON RICH ZONES SUBCUTANEOUSLY;
     10% COARSE FRAGMENTS
C5         78-89
        10YR5/4-SILT LOAM; MANY MEDIUM DISTINCT 7.5YR5/6 AND
     MANY MEDIUM DISTINCT 10YR6/1 MOTTLES; MASSIVE;
     FIRM;
     COMMON 10YR2/1 CONCRETIONS IN THE MATRIX;
     THIN VERY PATCHY 10YR6/1 COATINGS ON HORIZONTAL FACES
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Table A-5 (Cont'd). Description and Characterization Data for Coshocton Silt Loam (Watershed C06)

SOIL SERIES: COSHOCTON
SITE: CS-32

COUNTY: COSHOCTON
DATE: 8/26/76

DEPTH IN	HORIZON	CO FRAG %>2mm	PARTICLE SIZE DISTRIBUTION (%<2mm) SAND VC,C					SILT FI			CLAY FI		TEXT CLASS
			VC,C	M	FI	VFI	TOT	FI	VF	TOT	FI	TOT	
0- 6	AP1	0.4	0.8	1.5	6.3	6.2	14.8	40.1	9.5	62.6	7.1	22.6	SIL
6- 9	AP2	5.2	4.5	3.7	8.0	6.0	22.2	40.3	11.5	60.6	3.0	17.2	SIL
9-14	B11	14.0	10.4	3.9	8.6	5.6	28.5	33.6	9.9	50.8	4.5	20.7	SIL
14-21	B12T	14.6	8.5	4.6	14.6	5.5	33.2	29.0	8.1	44.0	6.9	22.8	L
21-30	B21T	5.9	4.3	3.5	7.1	6.5	21.4	31.8	7.8	51.6	12.5	27.0	CL
30-36	B22T	7.6	6.2	3.0	6.1	8.1	23.4	28.0	5.7	53.3	10.3	23.3	SIL
36-42	B31T	10.6	10.2	4.3	7.6	8.0	30.1	28.0	6.6	53.4	6.0	16.5	SIL
42-48	B32T	19.5	12.2	4.5	8.8	7.8	33.3	28.1	7.6	49.5	5.4	17.2	L
48-58	C1	5.4	14.9	5.2	9.6	7.9	37.6	29.3	7.9	47.8	4.0	14.6	L
58-64	C2	8.7	8.7	4.5	7.8	6.0	27.0	35.9	8.4	55.0	4.8	18.0	SIL
64-72	C3	15.7	13.4	6.2	10.9	6.0	36.5	29.7	7.8	48.0	4.8	15.5	L
72-78	C4	13.7	12.8	6.9	13.4	6.0	39.1	28.7	7.4	46.8	3.6	14.1	L
78-89	C5	12.2	9.2	3.1	7.1	5.7	25.1	35.4	9.3	57.3	5.0	17.6	SIL

DEPTH IN	pH WAT	pH CaCl	ORG C	EQ,% CALC	EQ,% DOLO	EQ,% CARB	EXCH CATIONS MEQ/100g H	Ca	Mg	K	SUM	BASE SAT,%
0- 6	5.2	4.7	2.44				10.3	6.5	1.4	0.30	18.5	44
6- 9	5.6	4.8	1.08				7.5	5.4	1.4	0.17	14.5	48
9-14	5.7	5.1	0.42				6.3	5.6	1.6	0.15	13.7	53
14-21	5.7	5.1	0.34				5.7	6.6	2.4	0.21	14.9	61
21-30	5.4	4.8	0.20				5.6	9.0	4.4	0.33	19.3	71
30-36	5.6	5.1	0.13				4.4	9.0	4.6	0.24	18.2	75
36-42	6.4	5.8	0.11				3.2	7.2	3.8	0.17	14.4	77
42-48	6.7	6.1	0.11				2.7	7.5	4.0	0.19	14.4	81
48-58	6.5	5.5	0.14				2.6	7.2	4.2	0.13	14.1	81
58-64	6.8	6.5	0.11				2.2	7.2	3.9	0.18	13.5	83
64-72	7.1	6.6	0.00	0.4	1.4	1.9	1.9	6.6	3.7	0.17	12.4	84
72-78	7.2	6.5	0.00	0.9	1.2	2.2	1.5	6.1	3.4	0.16	11.2	86
78-89	7.1	6.6	0.00	0.6	1.1	1.8	1.9	6.7	3.9	0.17	12.7	05

Table A-6. Description and Characterization Data for Lowell Silt Loam (Watershed M09)

```
SOIL TYPE: LOWELL SILT LOAM                COUNTY: MUSKINGUM  SITE: MS-11
PEDON CLASSIFICATION: FINE MIXED MESIC TYPIC HAPLUDALFS
LOCATION: 700.FT.S.AND.700.FT.W.OF.NE.CORNER SEC. 17 T.12N R.11W
PHYSIOGRAPHY: SIDESLOPE, BACKSLOPE                 ELEVATION: 1090
TOPOGRAPHY: MODERATELY STEEP        % SLOPE:          ASPECT: E
DRAINAGE: WELL                                     VEGETATION: WEEDS
COLLECTORS: SMECK/HALL/RIDDLE                      DATE: 2/77
PARENT MATERIALS: COLLUVIUM, SHALE


HORIZON   DEPTH
            IN
AP          0 -6
          10YR5/2-SILT LOAM: WEAK MEDIUM GRANULAR
      STRUCTURE: FRIABLE: FEW ROOTS:
      CLEAR SMOOTH BOUNDARY.
B1          6 -11
          10YR5/3-SILT LOAM: MANY COARSE FAINT 10YR5/4 MOTTLES:
      MODERATE FINE SUBANGULAR BLOCKY STRUCTURE: FRIABLE: FEW ROOTS:
      GRADUAL SMOOTH BOUNDARY.
B21T        11-15
          10YR5/4-SILTY CLAY LOAM: STRONG MEDIUM SUBANGULAR BLOCKY
      STRUCTURE: FIRM: FEW ROOTS:
      THIN PATCHY 10YR5/4 ARGILLANS ON FACES:
      CLEAR SMOOTH BOUNDARY.
B22T        15-22
          7.5YR5/4-HEAVY SILTY CLAY LOAM: MODERATE MEDIUM SUBANGULAR BLOCKY
      STRUCTURE: FIRM: FEW ROOTS:
      MEDIUM CONTINUOUS 5YR4/3 ARGILLANS ON FACES:
      CLEAR SMOOTH BOUNDARY.
B3T         22-28
          7.5YR4/4-LIGHT SILTY CLAY: MANY COARSE DISTINCT 5YR4/3 AND
      MANY COARSE DISTINCT 10YR5/3 MOTTLES: WEAK MEDIUM SUBANGULAR BLOCKY
      STRUCTURE: FIRM:
      THICK CONTINUOUS 5YR4/3 ARGILLANS ON VERTICAL FACES:
      COMMON 2.5Y6/2 MOTTLES IN THE MATRIX:
      CLEAR SMOOTH BOUNDARY.
C1          28-37
          10YR5/4-HEAVY SILTY CLAY LOAM: MANY COARSE DISTINCT 5Y6/3 MOTTLES:
      MASSIVE: FIRM:
      GRADUAL SMOOTH BOUNDARY.
C2          37-46
          2.5Y5/4-SILTY CLAY LOAM: MANY COARSE DISTINCT 10YR4/4 AND
      COMMON COARSE FAINT 2.5Y6/2 MOTTLES: MASSIVE:
      FRIABLE:
      GRADUAL SMOOTH BOUNDARY.
C3          46-54
          5YR3/3-SILTY CLAY: COMMON COARSE PROMINANT 10YR6/2 MOTTLES:
      MASSIVE: FIRM:


NOTE: COLLUVIUM CONTAINS A LOESS COMPONENT.
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Table A-6 (Cont'd). Description and Characterization Data for Lowell Silt Loam (Watershed MC9)

SOIL SERIES: LOWELL
SITE: MS-11

COUNTY: MUSKINGUM
DATE: 2/77

DEPTH IN	HORIZON	CO FRAG %>2mm	PARTICLE SIZE DISTRIBUTION (%<2mm) SAND VC.C	M	FI	VFI	TOT	SILT FI	VF	TOT	CLAY FI	TOT	TEXT CLASS
0- 6	AP	7.4	7.7	2.1	4.4	7.8	22.0	45.0	15.1	61.4	2.7	16.6	SIL
6-11	B1	13.6	5.5	1.4	3.8	8.8	19.5	41.2	14.4	59.8	3.9	20.7	SIL
11-15	B21T	1.7	1.9	0.3	0.9	4.0	7.1	44.4	14.9	58.7	11.2	34.2	SICL
15-22	B22T	4.5	2.6	0.5	0.6	0.6	4.3	45.4	23.0	48.2	16.9	47.5	SIC
22-28	B3T	0.0	0.8	0.6	1.5	2.0	4.9	38.0	16.2	43.0	22.0	52.1	SIC
28-37	C1	0.0	0.3	0.2	0.6	1.1	2.2	45.4	16.7	51.2	16.2	46.6	SIC
37-46	C2	0.0	0.1	0.1	0.7	1.5	2.4	40.5	15.9	50.3	16.3	47.3	SIC
46-54	C3	0.0	0.3	0.2	0.1	0.4	1.0	40.5	12.7	48.0	16.4	51.0	SIC

DEPTH IN	pH WAT	CaCl	ORG C	EQ.% CALC	DOLO	CARB	EXCH CATIONS MEQ/100g H	Ca	Mg	K	SUM	BASE SAT.%
0- 6	4.4	4.2	1.03				9.9	2.0	0.4	0.45	12.8	22
6-11	4.6	4.2	0.59				8.6	3.4	1.0	0.27	13.3	35
11-15	4.8	4.1	0.26				14.7	6.0	1.9	0.33	22.9	35
15-22	4.6	4.4	0.23				18.3	11.7	3.4	0.49	33.9	46
22-28	4.4	4.1	0.24				20.3	13.7	3.6	0.54	38.1	46
28-37	4.9	4.4	0.20				15.2	16.6	3.8	0.56	36.2	57
37-46	4.4	4.3	0.14				12.9	20.7	4.1	0.60	38.3	66
46-54	7.2	7.1		2.9	2.3	5.4						

Table A-7. Description and Characterization Data for Upshur Silt Loam (Watershed M09)

```
SOIL TYPE: UPSHUR SILT LOAM                  COUNTY: MUSKINGUM  SITE: MS-12
PEDON CLASSIFICATION: FINE MIXED MESIC TYPIC HAPLUDALFS
LOCATION: 900.FT.S.AND.700.FT.W.OF.NE.CORNER SEC. 17 T.12N R.11W
PHYSIOGRAPHY: NOSESLOPE, BACKSLOPE               ELEVATION: 1070.FT.
TOPOGRAPHY: MODERATELY STEEP         % SLOPE:         ASPECT: SW
DRAINAGE: WELL                                  VEGETATION: WEEDS
COLLECTORS: SMECK/HALL/RIDDLE                   DATE: 2/77
PARENT MATERIALS: SHALE

HORIZON   DEPTH
            IN
AP         0 -5
        10YR4/3-HEAVY SILT LOAM; WEAK MEDIUM GRANULAR
     STRUCTURE; COMMON ROOTS;
     CLEAR SMOOTH BOUNDARY.
B1T        5 -8
        10YR4/4-SILTY CLAY LOAM; MODERATE FINE SUBANGULAR BLOCKY
     STRUCTURE; FEW ROOTS;
     THIN VERY PATCHY 10YR4/4 ARGILLANS ON FACES;
     CLEAR SMOOTH BOUNDARY.
B21T       8 -13
        5YR4/3-CLAY; STRONG FINE SUBANGULAR BLOCKY
     STRUCTURE; FEW ROOTS;
     MEDIUM VERY PATCHY 5YR4/4 ARGILLANS ON FACES;
     COMMON 2.5Y5/4 ROCK GHOSTS IN THE MATRIX;
     CLEAR SMOOTH BOUNDARY.
B22T       13-18
        5YR4/3-CLAY; MODERATE MEDIUM SUBANGULAR BLOCKY
     STRUCTURE; FEW ROOTS;
     MEDIUM CONTINUOUS 5YR4/4 ARGILLANS ON FACES;
     COMMON 2.5Y5/4 ROCK GHOSTS IN THE MATRIX;
     GRADUAL SMOOTH BOUNDARY.
B31T       18-23
        7.5YR4/4-CLAY; COMMON MEDIUM DISTINCT 2.5Y5/4 MOTTLES;
     WEAK MEDIUM SUBANGULAR BLOCKY STRUCTURE; FEW ROOTS;
     THICK VERY PATCHY 5YR4/4 ARGILLANS ON FACES;
     ABRUPT SMOOTH BOUNDARY.
B32T       23-27
        2.5Y5/4-CLAY; COMMON FINE PROMINANT 7.5Y5/6 MOTTLES;
     WEAK MEDIUM SUBANGULAR BLOCKY STRUCTURE; FEW ROOTS;
     THICK VERY PATCHY 2.5Y3/2 ARGILLANS ON FACES;
     THICK PATCHY 5YR3/4 COATINGS ON FACES;
     ABRUPT SMOOTH BOUNDARY.
C1         27-35
        2.5Y6/4-SILTY CLAY LOAM; MASSIVE;
     FEW ROOTS;
     THICK PATCHY 7.5YR5/4 COATINGS ON FACES;
     DIFUSE SMOOTH BOUNDARY.
C2         35-42
        5Y6/3-SILTY CLAY LOAM; MASSIVE;
     THICK PATCHY 7.5YR5/4 COATINGS ON FACES;
     ABRUPT SMOOTH BOUNDARY.
C3         42-48
        2.5Y6/2-SILTY CLAY LOAM; MASSIVE;
     THICK PATCHY 7.5YR4/4 COATINGS ON FACES;
     ABRUPT SMOOTH BOUNDARY.
.C4        48-54
        2.5Y6/2-CLAY LOAM; MASSIVE;
     THICK PATCHY 7.5YR4/4 COATINGS ON FACES;
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Table A-7 (Cont'd). Description and Characterization Data for Upshur Silt Loam (Watershed M09)

SOIL SERIES: UPSHUR
SITE: MS-12

COUNTY: MUSKINGUM
DATE: 2/77

DEPTH IN	HORIZON	CO FRAG %>2mm	PARTICLE SIZE DISTRIBUTION (%<2mm)										TEXT CLASS
			SAND					SILT			CLAY		
			VC,C	M	FI	VFI	TOT	FI	VF	TOT	FI	TOT	
0- 5	AP	1.0	3.0	0.5	0.6	1.3	5.4	50.8	15.7	67.0	7.3	27.6	SICL
5- 8	B1T	0.0	1.1	0.3	0.6	1.1	3.1	50.8	17.5	61.9	10.6	35.0	SICL
8-13	B21T	0.0	0.7	0.3	0.5	0.4	1.9	46.7	17.2	51.0	19.2	47.1	SIC
13-18	B22T	0.0	0.6	0.3	0.6	0.6	2.1	37.4	14.5	42.2	26.3	55.7	SIC
18-23	B31T	0.0	0.3	0.5	1.5	1.0	3.3	27.2	12.7	32.5	31.5	64.2	C
23-27	B32T	0.0	0.1	0.2	0.8	1.1	2.2	40.3	18.2	45.7	19.4	52.1	SIC
27-35	C1	0.0	1.2	0.1	0.1	0.6	2.0	66.3	13.9	71.8	10.1	26.2	SIL
35-42	C2	0.0	2.1	0.3	0.3	1.5	4.2	65.5	17.3	69.5	8.0	26.3	SIL
42-48	C3	0.0	0.2	0.1	0.5	1.4	2.2	41.0	20.9	43.8	15.6	54.0	SIC
48-54	C4	0.3	1.4	0.2	0.6	0.9	3.1	60.9	31.4	62.9	7.1	34.0	SICL

DEPTH IN	pH		ORG C	EQ.%			EXCH CATIONS MEQ/100g					BASE SAT.%
	WAT	CaCl		CALC	DOLO	CARB	H	Ca	Mg	K	SUM	
0- 5	5.0	4.6	1.67				11.8	9.5	1.6	0.63	23.5	49
5- 8	5.1	4.6	0.82				11.8	14.1	1.9	0.44	28.2	58
8-13	4.8	4.5	0.46				13.9	17.0	2.5	0.55	34.0	59
13-18	4.7	4.5	0.37				16.5	21.6	2.4	0.66	41.2	59
18-23	4.9	4.7	0.27				16.2	29.8	3.1	0.85	50.0	67
23-27	5.5	5.4	0.21				8.4	30.9	4.1	0.61	44.0	80
27-35	5.5	5.4	0.14				6.0	19.8	2.4	0.33	28.5	78
35-42	5.4	5.2	0.12				5.4	21.8	2.3	0.33	29.8	81
42-48	6.8	6.3	0.32				2.9	36.4	2.4	0.55	42.3	93
48-54	7.4	6.8		23.1	0.5	23.6						

Table A-8. Description and Characterization Data for Westmoreland Silt Loam (Watershed M09)

```
SOIL TYPE: WESTMORE SILT LOAM            COUNTY: MUSKINGUM  SITE: MS-13
PEDON CLASSIFICATION: FINE SILTY MIXED MESIC TYPIC HAPLUDALFS
LOCATION: 1300 FT S AND 800 FT W OF NE CORNER. SEC. 17 T.12N R.11W
PHYSIOGRAPHY: NOSESLOPE, FOOTSLOPE             ELEVATION: 1010 FT.
TOPOGRAPHY: MODERATELY SLOPING      % SLOPE:      ASPECT: SW
DRAINAGE: WELL                                 VEGETATION: WEEDS
COLLECTORS: SMECK/HALL/RIDDLE                  DATE: 2/77
PARENT MATERIALS: WISCONSINAN LOESS, COLLUVIUM

HORIZON   DEPTH
            IN
AP          0 -3
        10YR4/2-SILT LOAM; MANY MEDIUM DISTINCT 10YR5/4 MOTTLES;
      WEAK MEDIUM GRANULAR STRUCTURE; COMMON ROOTS;
      CLEAR SMOOTH BOUNDARY.
B1          3 -8
        10YR5/4-SILT LOAM; WEAK FINE SUBANGULAR BLOCKY
      STRUCTURE; FEW ROOTS;
      CLEAR SMOOTH BOUNDARY.
B21T        8 -14
        10YR5/4-LIGHT SILTY CLAY LOAM; MODERATE MEDIUM SUBANGULAR BLOCKY
      STRUCTURE; FEW ROOTS;
      MEDIUM VERY PATCHY 10YR5/4 ARGILLANS ON FACES;
      CLEAR SMOOTH BOUNDARY.
B22T        14-20
        10YR5/4-SILTY CLAY LOAM; MODERATE MEDIUM SUBANGULAR BLOCKY
      STRUCTURE; FEW ROOTS;
      MEDIUM VERY PATCHY 10YR5/4 ARGILLANS ON FACES;
      CLEAR SMOOTH BOUNDARY.
B23T        20-28
        10YR5/4-LIGHT CLAY LOAM; FEW COARSE FAINT 10YR5/6 MOTTLES;
      WEAK MEDIUM SUBANGULAR BLOCKY STRUCTURE; FEW ROOTS;
      THIN VERY PATCHY 10YR5/4 ARGILLANS ON FACES;
      CLEAR WAVY BOUNDARY.
B24T        28-34
        10YR5/4-LIGHT SILTY CLAY LOAM; FEW FINE FAINT 10YR5/6 AND
      FEW FINE FAINT 10YR6/2 MOTTLES; WEAK MEDIUM SUBANGULAR BLOCKY
      STRUCTURE; FEW ROOTS;
      THIN VERY PATCHY 10YR5/4 ARGILLANS ON FACES;
      CLEAR SMOOTH BOUNDARY.
B31         34-42
        10YR5/4-SILT LOAM; FEW FINE FAINT 10YR5/6 AND
      FEW FINE FAINT 10YR6/2 MOTTLES; WEAK MEDIUM SUBANGULAR BLOCKY
      STRUCTURE;
      CLEAR SMOOTH BOUNDARY.
B32         42-48
        10YR5/4-SILTY CLAY LOAM; FEW FINE FAINT 10YR5/6 AND
      FEW MEDIUM FAINT 10YR6/2 MOTTLES; WEAK MEDIUM SUBANGULAR BLOCKY
      STRUCTURE;
      CLEAR SMOOTH BOUNDARY.
C           48-60
        10YR5/4-SILTY CLAY LOAM; FEW FINE FAINT 10YR5/6 AND
      FEW MEDIUM FAINT 10YR6/2 MOTTLES; MASSIVE
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Table A-8 (Cont'd). Description and Characterization Data for Westmoreland Silt Loam (Watershed M09)

SOIL SERIES: WESTMORE
SITE: MS-13

COUNTY: MUSKINGUM
DATE: 2/77

DEPTH IN	HORIZON	CO FRAG %>2mm	PARTICLE SIZE DISTRIBUTION (%<2mm)										TEXT CLASS
			SAND					SILT			CLAY		
			VC,C	M	FI	VFI	TOT	FI	VF	TOT	FI	TOT	
0- 3	AP	0.0	2.3	1.4	1.1	1.0	5.8	49.8	11.5	73.8	4.9	20.4	SIL
3- 8	B1	0.0	2.0	1.3	1.0	1.5	5.8	48.5	8.6	67.7	9.2	26.5	SIL
8-14	B21T	0.0	5.1	3.0	2.3	2.3	12.7	39.5	9.2	59.9	11.2	27.4	SICL
14-20	B22T	0.0	2.2	1.5	1.2	1.3	6.2	43.0	9.3	62.6	15.2	31.2	SICL
20-28	B23T	0.0	7.2	4.1	2.9	1.9	16.1	32.9	7.2	55.7	13.5	28.2	SICL
28-34	B24T	0.0	0.7	0.5	0.5	1.3	3.0	42.7	7.5	67.0	17.3	30.0	SICL
34-42	B31	0.0	1.5	1.0	0.9	1.6	5.0	42.9	8.7	65.6	13.5	29.4	SICL
42-48	B32	0.0	1.3	0.8	0.5	1.3	3.9	46.6	11.7	64.5	15.3	31.6	SICL
48-60	C	0.0	0.8	0.6	0.5	1.2	3.1	47.7	9.5	69.5	13.7	27.4	SICL

DEPTH IN	pH		ORG C	EQ,%			EXCH CATIONS MEQ/100g					BASE SAT,%
	WAT	CaCl		CALC	DOLO	CARB	H	Ca	Mg	K	SUM	
0- 3	4.8	4.3	2.88				17.5	3.8	1.3	0.93	23.5	25
3- 8	4.6	4.0	0.68				12.8	3.0	1.2	0.39	17.4	26
8-14	4.7	4.1	0.37				12.0	3.6	1.7	0.30	17.6	31
14-20	4.7	4.2	0.22				11.9	5.6	3.0	0.30	20.8	42
20-28	4.8	4.3	0.12				10.3	6.4	3.5	0.25	20.5	49
28-34	4.8	4.3	0.14				10.8	6.9	4.2	0.30	22.2	51
34-42	4.9	4.4	0.15				9.0	7.5	4.6	0.29	21.4	57
42-48	5.1	4.7	0.14				7.5	9.8	6.2	0.33	23.8	68
48-60	5.6	5.2	0.12				5.2	9.4	6.1	0.26	21.0	75

Table A-9. Description and Characterization Data for Licking Silt Loam (Watershed M09)

```
SOIL TYPE: LICKING SILT LOAM              COUNTY: MUSKINGUM  SITE: MS-14
PEDON CLASSIFICATION: FINE,MIXED,MESIC,AQUIC,HAPLUDALFS.
LOCATION: 2300FT.S.AND 1400FT.W.OF.NE.CORNER. SEC. 17 T.12N R.11W
PHYSIOGRAPHY: SLACKWATER TERRACE               ELEVATION: 970.FT.
TOPOGRAPHY: GENTLY SLOPING          % SLOPE:       ASPECT: SE
DRAINAGE: MODERATELY WELL                      VEGETATION: WEEDS
COLLECTORS: SMECK/HALL/RIDDLE                  DATE: 2/77
PARENT MATERIALS: WISCONSINAN LACUSTRINE. ,

HORIZON   DEPTH
            IN
AP         0 -6
         10YR4/3-SILT LOAM: WEAK MEDIUM GRANULAR
     STRUCTURE: FRIABLE: COMMON ROOTS:
     CLEAR SMOOTH BOUNDARY.
B1T        6 -12
         10YR4/4-SILT LOAM: WEAK FINE SUBANGULAR BLOCKY
     STRUCTURE: FRIABLE: FEW ROOTS:
     THIN VERY PATCHY 10YR4/4 ARGILLANS ON FACES:
     CLEAR SMOOTH BOUNDARY.
B21T       12-19
         10YR4/4-LIGHT SILTY CLAY LOAM: MODERATE FINE SUBANGULAR BLOCKY
     STRUCTURE: FRIABLE: FEW ROOTS:
     THIN PATCHY 10YR4/4 ARGILLANS ON FACES:
     CLEAR SMOOTH BOUNDARY.
B22T       19-26
         10YR5/4-SILTY CLAY LOAM: MODERATE MEDIUM SUBANGULAR BLOCKY
     STRUCTURE: FIRM: FEW ROOTS:
     THIN PATCHY 7.5YR4/4 ARGILLANS ON FACES:
     FEW 10YR2/1 CONCRETIONS IN THE MATRIX:
     CLEAR SMOOTH BOUNDARY.
IIB23T     26-34
         10YR5/4-CLAY: COMMON FINE FAINT 10YR5/6 AND
     FEW FINE DISTINCT 10YR5/2 MOTTLES: WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE: FIRM:
     MEDIUM VERY PATCHY 7.5YR4/4 ARGILLANS ON FACES:
     CLEAR SMOOTH BOUNDARY.
IIB24T     34-38
         10YR5/4-CLAY LOAM: COMMON MEDIUM FAINT 10YR5/6 AND
     FEW FINE DISTINCT 10YR5/2 MOTTLES: WEAK FINE SUBANGULAR BLOCKY
     STRUCTURE: FIRM:
     MEDIUM VERY PATCHY 10YR4/4 ARGILLANS ON FACES:
     MANY 10YR2/1 FERRO-MANGANS ON FACES:
     ABRUPT WAVY BOUNDARY.
IIB31T     38-41
         10YR5/4-CLAY: COMMON MEDIUM FAINT 10YR5/6 AND
     FEW MEDIUM DISTINCT 2.5Y5/2 MOTTLES: WEAK FINE SUBANGULAR BLOCKY
     STRUCTURE: FIRM:
     THIN VERY PATCHY 10YR4/4 ARGILLANS ON FACES:
     MANY 10YR2/1 FERRO-MANGANS ON FACES:
     ABRUPT WAVY BOUNDARY.
IIB32T     41-48
         10YR5/4-SILTY CLAY LOAM: COMMON MEDIUM FAINT 10YR5/6 AND
     FEW MEDIUM DISTINCT 2.5Y5/2 MOTTLES: WEAK MEDIUM SUBANGULAR BLOCKY
     STRUCTURE: FIRM:
     THIN VERY PATCHY 10YR4/4 ARGILLANS ON FACES:
     MANY 10YR2/1 FERRO-MANGANS ON FACES:
     CLEAR SMOOTH BOUNDARY.
IIB33T     48-57
         10YR5/4-SILTY CLAY LOAM: COMMON COARSE DISTINCT 10YR5/6 AND
     COMMON COARSE DISTINCT 2.5Y6/2 MOTTLES: WEAK MEDIUM PLATY
     PARTING TO WEAK MEDIUM ANGULAR BLOCKY STRUCTURE: FIRM:
     THIN VERY PATCHY 10YR4/4 ARGILLANS ON FACES:
     CLEAR SMOOTH BOUNDARY.
IIC        57-69
         2.5Y6/4-SILTY CLAY LOAM: COMMON COARSE DISTINCT 10YR5/6 AND
     COMMON COARSE DISTINCT 2.5Y6/2 MOTTLES: MASSIVE:
     FIRM:


NOTE:
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Table A-9 (Cont'd). Description and Characterization Data
Licking Silt Loam (Watershed M09)

SOIL SERIES: LICKING
SITE: MS-14

COUNTY: MUSKINGUM
DATE: 2/77

DEPTH IN	HORIZON	CO FRAG %>2mm	PARTICLE SIZE DISTRIBUTION (%<2mm) SAND VC,C	M	FI	VFI	TOT	SILT FI	VF	TOT	CLAY FI	TOT	TEXT CLASS
0- 6	AP	0.0	0.5	0.4	0.8	1.4	3.1	44.7	10.6	69.8	11.6	27.1	SICL
6-12	B1T	0.0	0.6	0.5	1.0	1.7	3.8	45.0	9.9	68.7	11.6	27.5	SICL
12-19	B21T	0.0	0.9	0.8	1.5	2.1	5.3	42.1	9.9	66.3	13.6	28.4	SICL
19-26	B22T	0.0	1.7	1.2	2.0	2.1	7.0	36.7	10.0	54.3	20.1	38.7	SICL
26-34	IIB23T	0.0	1.0	0.6	0.0	5.0	6.6	29.7	9.9	42.2	28.7	51.2	SIC
34-38	IIB24T	0.0	1.6	0.7	0.0	7.7	10.0	28.6	10.1	40.8	26.6	49.2	SIC
38-41	IIB31T	0.0	0.5	0.4	0.0	2.7	3.6	39.3	15.0	45.7	19.8	50.7	SIC
41-48	IIB32T	0.0	2.7	1.3	0.0	5.1	9.1	35.0	15.4	41.9	22.9	49.0	SIC
48-57	IIB33T	1.9	1.6	0.5	1.1	2.2	5.4	43.8	16.8	52.1	10.6	42.5	SIC
57-69	IIC	0.5	1.2	0.4	1.0	1.9	4.5	53.4	21.9	58.6	6.5	36.9	SICL

DEPTH IN	pH WAT	CaCl	ORG C	EQ.% CALC	DOLO	CARB	EXCH CATIONS MEQ/100g H	Ca	Mg	K	SUM	BASE SAT.%
0- 6	5.8	5.7	1.19				4.9	7.7	1.5	0.22	14.3	65
6-12	4.8	4.5	0.35				8.0	7.0	1.9	0.23	17.1	53
12-19	4.8	4.6	0.22				8.5	7.1	2.9	0.23	18.7	54
19-26	4.9	4.6	0.19				10.2	10.0	5.3	0.33	25.8	60
26-34	4.9	4.4	0.16				14.9	16.0	8.3	0.45	39.7	62
34-38	5.0	4.6	0.15				13.1	19.2	9.1	0.48	41.9	68
38-41	5.1	4.6	0.13				11.0	22.4	10.1	0.50	44.0	75
41-48	5.6	5.1	0.20				9.0	28.6	10.4	0.36	48.4	81
48-57	6.5	6.0	0.14				4.2	27.2	10.1	0.33	41.8	89
57-69	7.6	7.1	0.00	7.0	1.7	8.8						

Table A-10. Description and Characterization Data for Brookside Silty Clay Loam (Watershed M09)

```
SOIL TYPE: BROOKSIDE SILTY CLAY LOAM      COUNTY: MUSKINGUM  SITE: MS-15
PEDON CLASSIFICATION: FINE.MIXED.MESIC.TYPIC.HAPLUDALF
LOCATION: 1500.FT.S.AND.1300.FT.W.OF.THE.NE.CORNER SEC. 17 T.12N R.11W
PHYSIOGRAPHY: SIDESLOPE. FOOTSLOPE                ELEVATION: 1010
TOPOGRAPHY: MODERATELY SLOPING      % SLOPE:        ASPECT: SE
DRAINAGE: WELL                                    VEGETATION: WEEDS
COLLECTORS: SMECK/HALL/RIDDLE                     DATE: 2/77
PARENT MATERIALS: COLLUVIUM. .


HORIZON   DEPTH
            IN
AP          0 -9
           10YR4/2-SILTY CLAY LOAM: MODERATE MEDIUM SUBANGULAR BLOCKY
      STRUCTURE: COMMON ROOTS:
      CLEAR SMOOTH BOUNDARY.
B2          9 -17
           10YR4/3-SILTY CLAY: MODERATE MEDIUM SUBANGULAR BLOCKY
      STRUCTURE: FEW ROOTS:
      CLEAR SMOOTH BOUNDARY.
B3T         17-27
           10YR4/4-SILTY CLAY: WEAK FINE SUBANGULAR BLOCKY
      STRUCTURE: FEW ROOTS:
      THIN VERY PATCHY 10YR3/4 ARGILLANS ON FACES:
      CLEAR SMOOTH BOUNDARY.
IIAB        27-35
           10YR5/4-SILTY CLAY LOAM: MODERATE MEDIUM SUBANGULAR BLOCKY
      STRUCTURE: FEW ROOTS:
      MEDIUM VERY PATCHY 10YR4/4 ARGILLANS ON FACES:
      CLEAR SMOOTH BOUNDARY.
IIB21T      35-43
           10YR5/4-CLAY:
      WEAK FINE SUBANGULAR BLOCKY STRUCTURE:
      THICK VERY PATCHY 10YR4/2 ARGILLANS ON FACES:
      THIN VERY PATCHY 10YR4/4 ARGILLANS ON FACES:
      CLEAR SMOOTH BOUNDARY.
IIB22T      43-49
           10YR5/4-CLAY:
      WEAK FINE SUBANGULAR BLOCKY STRUCTURE:
      THICK VERY PATCHY 10YR4/2 ARGILLANS ON FACES:
      THIN VERY PATCHY 10YR4/4 ARGILLANS ON FACES:
      ABRUPT SMOOTH BOUNDARY.
IIC1CA      49-53
           10YR6/3-SILTY CLAY LOAM:
      WEAK FINE SUBANGULAR BLOCKY STRUCTURE:
      FEW 10YR3/4 FERRO-MANGANS ON FACES:
      ABRUPT SMOOTH BOUNDARY.
IIC2CA      53-59
           10YR6/3-SILTY CLAY LOAM: FEW FINE FAINT 10YR6/6 MOTTLES:
      WEAK COARSE PLATY PARTING TO WEAK FINE
      SUBANGULAR BLOCKY STRUCTURE:
      FEW 10YR3/4 FERRO-MANGANS ON FACES:
      ABRUPT SMOOTH BOUNDARY.
IIIAB       59-64
           10YR4/2-SILT LOAM: MODERATE COARSE PLATY
      PARTING TO MODERATE FINE SUBANGULAR BLOCKY STRUCTURE:
      CLEAR SMOOTH BOUNDARY.
IIIC1CA     64-67
           10YR6/3-SILTY CLAY LOAM:
      WEAK MEDIUM SUBANGULAR BLOCKY STRUCTURE:
      CLEAR SMOOTH BOUNDARY.
IIIC2CA     67-74
           10YR6/3-SILT LOAM: FEW FINE FAINT 10YR5/6 MOTTLES:
      MASSIVE:
```

Table A-10 (Cont'd). Description and Characterization Data for Brookside Silty Clay Loam (Watershed M09).

SOIL SERIES: BROOKSIDE
SITE: MS-15

COUNTY: MUSKINGUM
DATE: 2/77

DEPTH IN	HORIZON	CO FRAG %>2mm	PARTICLE SIZE DISTRIBUTION (%<2mm)										TEXT CLASS
			SAND					SILT			CLAY		
			VC.C	M	FI	VFI	TOT	FI	VF	TOT	FI	TOT	
0- 9	AP	5.0	4.0	2.4	11.3	11.5	29.2	31.2	11.3	39.5	12.7	31.3	CL
9-17	B2	9.1	1.4	1.1	7.3	13.4	23.2	28.0	9.8	34.3	22.0	42.5	C
17-27	B3T	0.1	0.5	0.2	1.6	3.7	6.0	29.0	12.1	34.4	30.3	59.6	C
27-35	IIAB	0.4	1.4	1.4	11.1	17.3	31.2	20.7	8.3	29.2	20.9	39.6	CL
35-43	IIB21T	0.0	0.1	0.3	3.0	3.6	7.0	26.0	11.3	30.2	31.7	62.8	C
43-49	IIB22T	0.1	0.4	0.1	0.2	0.4	1.1	36.7	12.6	38.3	22.9	60.6	C
49-53	IIC1CA	2.0	3.6	0.5	0.6	0.5	5.2	47.5	23.8	48.6	17.0	46.2	SIC
53-59	IIC2CA	2.9	2.4	0.6	0.8	0.7	4.5	57.3	31.5	58.2	12.3	37.3	SICL
59-64	IIIAB	0.1	0.6	0.4	1.8	3.9	6.7	51.7	22.0	58.2	4.2	35.1	SICL
64-67	IIIC1CA	0.3	1.2	0.4	0.7	0.9	3.2	52.4	29.0	56.2	5.8	40.6	SIC
67-74	IIIC2CA	0.2	2.9	0.7	1.1	1.1	5.8	54.8	27.0	56.7	5.2	37.5	SICL

DEPTH IN	pH		ORG	EQ.%			EXCH CATIONS MEQ/100g					BASE SAT.%
	WAT	CaCl	C	CALC	DOLO	CARB	H	Ca	Mg	K	SUM	
0- 9	5.9	5.6	1.28				8.7	18.0	3.4	0.66	30.8	71
9-17	5.7	5.4	0.81				6.3	24.0	3.9	0.78	35.0	81
17-27	7.3	6.8	0.27	8.1	1.9	10.1						
27-35	7.2	6.4	0.21	0.8	0.7	1.5	1.8	29.3	2.5	0.63	34.2	94
35-43	6.9	6.7	0.25	0.3	0.3	0.7	1.8	33.7	2.9	0.80	39.2	95
43-49	7.4	6.9	0.16	9.8	1.1	11.0						
49-53	7.7	7.1	1.48	46.8	1.7	48.6						
53-59	7.7	7.2		5.4	2.2	7.8						
59-64	7.6	7.3		2.8	0.7	3.6						
64-67	7.8	7.4		37.3	3.2	40.7						
67-74	7.9	7.5		38.3	3.5	42.1						

APPENDIX B

Table B-1. Physical and Chemical Data for Geologic Core at C06.

Table B-2. Physical and Chemical Data for Geologic Core at M09.

Table B-3. Physical and Chemical Data for Geologic Core at J11.

Table B-4. Physical and Chemical Data for Geologic Core at J08.

Table B-1. Physical and Chemical Data for Geologic Core at C06

PARTICLE SIZE DISTRIBUTION (PERCENT)

		SAND (mm)						SILT ( )			CLAY ( )			
Elev. (FT.)	SAMPLE DESIG.	VERY COARSE 1-2	COARSE .5-1	MEDIUM .25-.5	FINE .1-.25	VERY FINE .05-1	TOTAL .05-2	FINE 2-20	COARSE 20 50	TOTAL 2-50	FINE .2	COARSE .2-2	TOTAL 2	TEXTURAL CLASS
943.1	6B	0.5	1.3	0.4	0.5	0.5	3.2	70.6	-1.0	69.6	3.1	24.1	27.1	sicl
938.6	6C	12.5	20.5	7.6	10.0	4.3	55.0	17.4	2.4	19.7	4.2	21.0	25.3	scl
937.1	7	--	--	--	--	--	--	--	--	--	--	--	--	COAL
934.1	8A	5.0	8.9	4.9	15.8	19.5	54.2	19.3	15.3	34.6	1.3	9.8	11.2	sl
930.1	8B	0.1	0.1	0.0	0.5	5.9	6.7	55.4	16.9	72.3	2.7	18.3	21.0	sil
923.1	9	0.4	0.7	0.4	4.0	15.5	21.1	41.2	17.8	59.0	2.3	17.6	19.9	sil
915.1	10	3.8	6.9	1.6	3.8	12.3	28.6	37.9	16.2	54.0	2.8	14.5	17.3	sil
908.1	11	1.3	3.1	1.9	10.8	16.3	33.4	34.5	16.0	50.5	2.5	13.5	16.0	sil
898.1	12A	2.4	5.4	6.9	44.4	16.6	75.7	9.8	6.6	16.4	1.0	6.8	7.8	sl
890.1	12B	7.5	12.6	4.6	11.8	18.4	55.0	20.4	11.5	31.9	1.9	11.2	13.1	sl
853.1	C06-14	1.2	2.4	0.6	1.2	7.1	12.6	52.6	18.4	71.0	2.0	14.4	16.4	sil
795.0	17	7.4	13.9	6.9	14.0	15.8	58.1	20.6	11.8	32.4	0.8	8.6	9.4	sl
777.5	18	--	--	--	--	--	--	--	--	--	--	--	--	COAL
773.0	19	0.1	0.2	0.2	0.5	1.9	2.9	64.1	10.5	74.6	3.2	19.2	22.4	sil
768.5	20	0.0	0.2	0.1	0.7	1.1	2.2	61.8	-1.0	60.8	3.4	33.6	37.0	sicl
767.0	21	32.1	26.5	9.2	13.3	5.2	86.4	11.3	1.5	12.8	0.2	0.6	0.8	S
765.0	22	--	--	--	--	--	--	--	--	--	--	--	--	COAL
764.0	23	--	--	--	--	--	--	--	--	--	--	--	--	COAL

Table B-1 (Cont'd) Physical and Chemical Data for Geologic Core at C06.

SAMPLE DESIG.	pH 1:1 (H_2O)	pH 1:2 ($CaCl_2$)	TOTAL SULFUR %	CAL-CITE %	DOLO-MITE %	$CaCO_3$ EQUIVA-LENT %	ROCK DESCRIPTION
C06-4	6.7	6.7	1.4	--	--	--	Grey Siltstone
C06-6A	6.1	5.5	5.4	--	--	--	Varigate Shale
C06-6B	7.0	6.9	0.4	--	--	--	Grey Shale
C06-6C	2.5	2.8	6.0	--	--	--	Grey-Black Clay
C06-7	3.1	3.2	2.7	--	--	--	#6 COAL
C06-8A	8.0	7.5	0.2	0.1	0.8	0.9	Underclay
C06-8B	7.7	7.5	0.2	0.1	1.2	1.4	Underclay
C06-9	8.2	7.6	0.03	0.2	2.0	2.3	Grey Silty Shale
C06-10	7.8	7.6	0.1	0.2	.26	3.1	Black Carbonaceous Shale
C06-11	8.2	7.8	0.02	0.0	1.6	1.7	Grey Silty Shale
C06-12A	7.4	7.0	0.3	-0.2	2.5	2.5	Grey Thinly bedded sandstone
C06-12B	7.5	6.9	0.2	--	--	--	Grey Black Sanstone
C06-14	8.4	7.7	0.02	0.0	0.9	1.0	Grey Siltstone
17	7.4	7.0	0.2	0.2	5.5	6.2	L. Grey SS W/ Carb. Silty Shale
18	4.9	5.1	3.5	--	--	--	COAL
19	6.6	6.4	0.4	--	--	--	Grey Sandstone
20	4.1	4.1	1.9	--	--	--	Clay
21	7.9	7.5	0.3	70.5	14.7	86.4	Dark Limestone
22	8.1	7.5	1.0	0.4	1.5	2.1	COAL (Bedford)
23	8.4	7.7	0.8	0.0	0.3	0.4	COAL (Shale)

Table B-2. Physical and Chemical Data for Geologic Core at M09.

		PARTICLE SIZE DISTRIBUTION (PERCENT)												
		SAND (mm)						SILT ( )			CLAY ( )			
ELEV. (Ft.)	SAMPLE DESIG.	VERY COARSE 1-2	COARSE .5-1	MEDIUM .25-.5	FINE .1-.25	VERY FINE .05-.1	TOTAL .05-2	FINE 2-20	COARSE 20-50	TOTAL 2-50	FINE .2	COARSE .2-2	TOTAL 2	TEXTURAL CLASS
1107	F09-2A	10.8	14.7	7.0	15.0	21.2	68.8	11.9	11.8	23.7	1.0	6.4	7.4	sl
1101	2E	2.5	7.8	2.1	1.1	0.1	13.6	61.2	1.1	62.3	2.9	21.2	24.1	sil
1097	2C	0.1	0.4	0.3	1.3	4.0	6.2	64.4	8.4	72.8	2.2	18.8	21.0	sil
1096	2D	0.7	1.2	1.1	2.5	2.9	8.6	61.4	6.3	67.7	2.5	21.2	23.7	sil
1095	3	1.6	4.0	1.7	1.9	1.0	10.4	47.4	1.6	49.0	4.4	36.2	40.6	sicl
1094	4	0.4	1.1	0.9	1.9	2.6	6.9	61.1	4.9	66.0	2.4	24.6	27.1	sicl
1093	5	35.9	27.3	8.4	10.3	3.6	85.6	7.2	1.2	8.5	0.7	5.2	5.9	ls
1090	6A	1.7	4.3	1.8	2.2	2.0	12.2	60.2	4.0	64.1	1.8	21.9	23.7	sil
1085	6B	1.2	1.3	0.8	2.8	9.5	15.8	55.4	11.1	66.6	1.5	16.1	17.6	sil
1079	6C	1.8	2.8	0.6	0.5	0.7	6.3	67.7	8.3	76.0	1.9	15.7	17.7	sil
1075	6D	4.6	11.5	3.4	2.0	0.8	22.3	48.9	0.2	49.0	3.3	25.3	28.6	cl
1069	6E	26.3	27.9	9.9	12.9	4.5	81.6	9.0	2.7	11.7	0.6	6.0	6.6	ls
1059	6F	2.8	3.4	1.2	2.3	4.4	14.3	61.4	7.0	68.4	1.9	15.4	17.3	sil
1044	6G	5.4	25.4	10.0	9.4	2.5	52.7	20.3	2.2	22.5	5.3	19.5	24.8	scl
1039	6H	1.0	7.8	5.6	6.8	3.7	24.9	33.0	4.2	37.2	6.7	31.1	37.8	cl
1031	7	18.6	28.1	9.8	10.1	3.0	69.7	19.7	2.0	21.8	2.8	5.7	8.5	sl
1014	8	2.5	8.7	9.6	45.9	20.9	87.6	5.1	4.1	9.2	0.7	2.5	3.2	s
997	9	8.6	10.6	3.4	4.2	2.3	29.1	35.5	2.4	37.9	4.1	28.8	33.0	cl
994	10	-	-	-	-	-	-	-	-	-	-	-	-	COAL
991	11	0.3	0.6	0.4	1.0	1.1	3.6	63.1	3.6	66.6	2.9	26.9	29.8	sicl
988	12	0.8	0.9	0.5	1.2	1.7	5.2	68.8	8.8	77.6	2.6	14.5	17.1	sil
982	13	31.5	27.8	8.6	10.8	3.7	82.5	10.0	1.3	11.3	0.8	5.4	6.2	ls
965	14	0.3	1.7	2.1	3.1	1.6	8.9	74.6	3.2	71.4	1.9	17.7	19.6	sil
947	15	9.2	9.9	2.2	3.3	6.6	31.4	38.0	17.0	55.0	2.2	11.3	13.5	sil
936	17	1.4	1.1	0.5	1.4	1.4	5.9	63.1	2.4	65.5	2.9	25.7	28.6	sicl
933	18	6.4	5.5	2.3	3.9	2.4	20.6	50.5	3.2	53.7	3.3	22.4	25.7	scl
926	19	13.8	12.3	3.1	5.9	3.6	38.9	39.7	5.8	45.6	2.1	13.4	15.5	l
912	20	-	-	-	-	-	-	-	-	-	-	-	-	COAL
911	21	1.4	4.1	1.9	4.1	5.3	17.0	47.0	6.8	53.8	2.8	26.4	29.2	sicl

Table B-2. (Cont'd) Physical and Chemical Data for Geologic Core at M09.

SAMPLE DESIG.	pH 1:1 (H_2O)	pH 1:2 ($CaCl_2$)	TOTAL SULFUR %	CAL-CITE %	DOLO-MITE %	$CaCO_3$ EQUIVA-LENT %	ROCK DESCRIPTION
2A	8.0	7.5	0.06	1.0	0.5	1.5	Tar - Yellow Quartz Sandstone
2B	8.0	7.7	0.01	0.4	0.8	1.2	Red Clay Shale
2C	8.0	7.8	0.03	15.3	1.6	17.0	Black Clay Shale
2D	8.1	7.7	0.03	10.0	2.0	12.1	Red Clay Shale
3	8.1	7.6	0.06	0.3	0.7	1.1	Coaly Shale
4	8.1	7.8	0.04	3.3	0.6	3.9	Grey Underclay
5	8.4	7.8	0.1	73.9	16.3	91.6	Grey Limestone
6A	8.5	7.8	0.03	53.0	6.8	60.4	Pink Shale
6B	8.1	7.9	0.15	24.1	1.8	26.0	Dark Red Shale
6C	8.2	8.0	0.05	1.2	1.7	3.0	Green Grey Shale
6D	8.3	8.0	0.02	25.3	11.0	37.2	Dark Red Shale
6F	9.0	7.9	.68	0.2	0.5	0.8	Green Grey Shale
6G	9.1	8.3	0.02	8.2	10.1	19.2	Dark Red Shale
6H	8.7	8.5	0.12	2.6	1.0	3.7	Dark Grey Shale
7	9.3	8.8	0.03	58.5	14.5	74.2	Grey Limestone
8	9.1	8.0	0.08	1.2	0.9	2.1	Green Sandstone
9	6.0	6.0	6.2	--	--	--	Carbonaceous Shale
10	8.7	7.7	3.4	0.4	3.1	3.8	Coal
11	8.8	8.6	2.6	4.3	5.6	10.5	Grey Underclay
12	9.2	9.0	1.4	1.3	1.6	3.1	Grey Shale
13	9.8	8.4	0.1	70.0	15.0	86.2	Limestone
14	9.6	9.1	5.2	0.6	1.0	1.6	Grey Shale w/ Pyrite
15	9.4	8.3	0.1	0.1	4.0	4.2	Grey Sandy Shale
17	9.3	9.0	0.8	5.8	3.1	9.2	Grey Underclay
18	9.2	9.1	0.1	8.4	10.6	19.8	Red-Green Shale
19	9.4	8.4	0.05	0.1	6.9	7.6	Grey Siltstone
20	5.5	5.7	8.6	--	--	--	Pitt #8 Coal
21	9.2	8.6	1.22	38.8	7.0	46.4	Underclay

Table B-3. Physical and Chemical Data for Geologic Core at J11.

PARTICLE SIZE DISTRIBUTION (PERCENT)

		SAND (mm)						SILT ( )			CLAY ( )			
Depth	SAMPLE DESIG.	VERY COARSE 1-2	COARSE .5-1	MEDIUM .25-.5	FINE .1-.25	VERY FINE .05-.1	TOTAL .05-2	FINE 2-20	COARSE 20-50	TOTAL 2-50	FINE .2	COARSE .2-2	TOTAL 2	TEXTURAL CLASS
50	J11-3	0.7	6.2	30.6	37.3	6.9	81.7	8.3	4.9	13.2	0.9	4.2	5.1	ls
53	4	--	--	--	--	--	--	--	--	--	--	--	--	COAL
56	5	18.2	23.2	5.7	7.4	2.9	57.4	20.6	2.4	23.0	3.2	16.4	19.6	csl
90	9	20.4	20.2	8.3	14.5	11.2	74.6	12.7	7.2	19.9	0.4	5.1	5.5	cls
94	10	--	--	--	--	--	--	--	--	--	--	--	--	COAL
95	11	17.5	17.9	5.1	5.5	3.7	49.7	27.5	5.0	32.5	1.4	16.4	17.8	l
100	12	19.3	21.7	6.0	5.2	1.1	53.3	18.8	1.6	20.4	3.3	23.0	26.3	scl
142	19	5.9	7.6	2.6	3.1	1.3	20.5	43.1	0.8	43.9	4.9	30.7	35.6	cl
156	22	27.0	26.2	8.1	9.6	3.0	73.9	16.0	2.9	18.9	0.6	6.6	7.2	csl
199	25	5.1	13.3	3.7	3.8	1.3	27.2	29.7	0.6	30.3	6.2	36.3	42.5	c
203	26	--	--	--	--	--	--	--	--	--	--	--	--	COAL
207	27	12.5	14.9	3.9	5.2	2.8	39.3	30.6	1.2	31.8	3.3	25.6	28.9	cl
215	J11-28	3.4	2.8	0.2	0.2	0.3	6.9	68.4	1.6	70.0	2.4	20.7	23.7	Sil
295	37	--	--	--	--	--	--	--	--	--	--	--	--	COAL
297.5	38	22.9	29.6	8.2	11.9	4.4	77.0	13.1	3.5	16.6	1.2	5.2	6.4	lcs
300	39	0.8	1.8	0.7	1.6	3.5	8.4	56.7	8.4	65.1	2.5	24.0	26.5	sil

Table B-3.(Cont'd) Physical and Chemical Data for Geologic Core at J11.

SAMPLE DESIG.	pH 1:1 (H_2O)	pH 1:2 ($CaCl_2$)	TOTAL SURFUR %	CAL-CITE %	DOLO-MITE %	$CaCO_3$ EQUIV. %	ROCK DESCRIPTION
J11-3	7.9	7.4	0.85	3.7	2.3	6.2	Grey Micaoeous Sandstone
4	6.7	6.5	1.4	--	--	--	Waynesburg #11 Coal
5	4.3	4.2	1.5	--	--	--	Dark Grey Coaly Clay Shale
9	7.3	7.4	1.1	22.9	6.3	29.7	Grey Shale w/ Limestone
10	6.3	6.2	2.2	--	--	--	Uniontown #10 Coal
11	8.7	7.9	0.24	41.4	5.25	47.1	Carbonaceous Shale
12	9.2	8.3	0.56	43.5	5.2	49.2	Black Grey Shaley Limestone
19	8.2	7.9	1.60	1.7	1.8	3.7	Shale, Siltstone and marly Limestone
22	9.6	8.2	0.15	58.0	10.7	69.6	Black, Grey Limestone
25	9.1	8.8	1.29	1.2	2.3	3.6	Shale
26	7.4	7.0	5.16	--	--	--	Sewockley #9 Coal
27	8.5	8.0	0.99	0.5	1.4	2.0	Coaly Shale
J11-28	6.1	5.9	1.5	--	--	--	Grey Shale and Siltstone
37	5.2	4.7	1.8	--	--	--	Pittsburg #8 Coal
38	3.8	3.7	3.4	--	--	--	Coaly Shale
39	8.6	8.2	1.53	12.9	7.1	20.7	Grey Black Limestone

Table B-4. Physical and Chemical Data for Geologic Core at J08.

PARTICLE SIZE DISTRIBUTION (PERCENT)

		SAND (mm)						SILT ( )			CLAY ( )			
DEPTH (Ft.)	SAMPLE DESIG.	VERY COARSE 1-2	COARSE .5-1	MEDIUM .25-.5	FINE .1-.25	VERY FINE .05-.1	TOTAL .05-2	FINE 2-20	COARSE 20-50	TOTAL 2-50	FINE .2	COARSE .2-2	TOTAL 2	TEXTURAL CLASS
51	J08-4	4.9	6.3	1.8	2.0	0.8	15.8	62.4	2.3	64.7	1.2	18.3	19.5	sil
88	10	20.9	27.6	8.2	9.5	2.4	68.6	19.2	1.9	21.1	1.3	9.0	10.3	csl
99.5	12	16.4	29.9	8.7	7.3	0.6	62.9	18.6	0.7	19.3	2.0	15.8	17.8	csl
115	14A	23.2	29.2	8.2	10.6	3.6	74.8	9.1	2.1	11.2	4.5	9.5	14.0	csl
120.5	14B	17.8	24.4	8.8	13.5	5.6	70.1	14.4	4.7	19.1	1.4	9.4	10.8	csl
125	15	--	--	--	--	--	--	--	--	--	--	--	--	COAL
126	16	20.0	17.7	4.5	5.4	4.6	52.2	27.0	10.0	37.0	0.5	10.3	10.8	csl
147.5	17	17.4	12.1	3.4	5.1	8.4	46.4	29.8	12.6	42.4	0.1	11.1	11.2	l
160.5	18	11.7	18.2	8.9	21.0	21.7	81.5	9.0	6.9	15.9	0.7	1.9	2.6	lcs
174.5	20	21.7	27.5	8.8	11.8	5.4	75.2	13.5	3.9	17.4	0.2	7.2	7.4	csl
193.5	21	0.3	0.7	0.3	0.4	0.4	2.1	45.1	0.5	45.6	3.2	49.1	52.3	sic
214	25	1.7	2.9	1.9	4.2	4.0	14.7	57.0	7.4	64.4	2.8	18.1	20.9	sil
216	J08-26	--	--	--	--	--	--	--	--	--	--	--	--	COAL
218.5	27	25.2	23.4	7.0	10.3	5.2	71.1	15.4	4.2	19.6	1.2	8.1	9.3	csl
222	28	--	--	--	--	--	--	--	--	--	--	--	--	COAL
226	29	6.2	9.5	3.1	5.2	4.0	28.0	39.7	6.2	45.9	2.2	23.9	26.1	l

Table B-4. (Cont'd) Physical and Chemical Data for Geologic Core at J08.

SAMPLE DESIG.	pH 1:1 (H_2O)	pH 1:2 ($CaCl_2$)	TOTAL SULFUR %	CAL-CITE %	DOLO-MITE %	$CaCO_3$ EQUIV. %	ROCK DESCRIPTION
J08-4	8.0	7.8	0.17	25.0	4.0	29.3	Olive-Grey Shale and Siltstone
10	8.5	8.1	0.24	23.5	4.1	27.9	Olive-Grey Shale
12	8.3	8.0	0.32	61.6	6.7	68.8	Olive-Grey Shale and Limestone
14A	8.6	8.1	0.74	33.3	8.8	42.9	Grey Shales and Limestone Nodules
14B	8.7	7.9	0.80	17.9	3.8	22.1	Grey Shales and Limestone Nodules
15	7.4	7.1	3.35	--	--	--	Sewickley #9 Coal
16	8.7	7.8	0.66	0.2	1.0	0.9	Grey Sandstone, Silt Banded
17	9.4	8.1	0.61	23.7	9.7	34.2	Grey Carbonaceous Shale
18	6.4	6.6	1.34	--	--	--	Grey Carbonaceous Sandstone
20	9.0	8.0	0.24	59.1	6.4	66.0	Grey Limestone and Shale
21	9.4	9.1	0.04	3.2	3.6	7.0	Green Shale, Coaly Base
25	8.7	8.1	1.91	7.1	6.7	14.4	Black Calcareous Shale
J08-26	5.4	5.1	12.0	--	--	--	Coal
27	5.2	4.7	9.6	--	--	--	Coaly Shale
28	5.8	5.3	3.6	--	--	--	Pittsburg #8 Coal
29	7.3	7.5	3.13	-0.2	0.6	0.5	Grey and Green Shale

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